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TOPICS IN SOLAR COSMIC RAY AND X-RAY PRODUCTION

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TOPICS IN SOLAR COSMIC RAY AND X-RAY PRODUCTION

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This talk is concerned with topics related to energetic interplanetary particle and X-ray production by the sun. It is based upon certain observations of solar protons, electrons, and X-rays resulting from some Goddard experiments using the IMP, OGO, and OSO series of satellites. Some of these measurements I was connected with and some I am transmitting for others. Together, these observations help to provide a basic phenomenology needed for the theorizing of an accurate and complete picture of particle acceleration at the sun.

The present results contrast to the solar particle data available a decade ago in that these were gathered using instruments with lower energy sensitivity, which were flown outside the earth's atmosphere and magnetosphere, and were exposed throughout much of the solar cycle. These data show that solar energetic particles are produced more often than only in the larger flares and suggest that they are produced in more than one manner. The first coherent and simple picture displaying several of the observed varieties of solar cosmic ray events is shown in Figure 1. The low-energy proton time history, recorded with McDonald's instruments on Explorer XII, is composed of the September 28, 1961 solar flare increase, the September 30 "energetic storm particles," and, on the following solar rotation, the 27-day delayed or recurrence event.[1] This result, now ancient history, provided the first classification of

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solar particle events. The categorization was made upon the way the particles are transported from the sun to the earth: in order, in a manner determined by particle velocity, in a manner determined by the motion of the enhanced solar plasma, and in a manner determined by the rotation of the sun. The time scales for intensity maximum are accordingly hours, days, and weeks after the flare. This classification scheme has been somewhat redefined over the intervening years in that each category of events may be extended to include more than one type; for example, flare events may or may not be diffusive, 27-day events can be recurrent from sites of earlier flares or can be of a quiet-time, corotation variety, and the picture of storm particle events also can be confused, as we shall note later. Also, such questions as interplanetary conditions and relative detector solar longitude can make the unique classification of a given event ambiguous, or at least arguable.

The nature of the primary solar flare particle event at its source is itself one of the most fundamental and yet presently unsettled questions. Figure 2, also from our studies of the same events of September 1961, shows the intensity histories of the initial flare event, as studied with differential spectral resolution over the dynamic range of observation from just above 1 MeV to nearly 1 BeV. For nearly these three orders of magnitude of proton kinetic energy, all the plots of particle intensity versus path length are seen to fit a common curve. Further, this common distribution is not an arbitrary or forced fit to the data, but results from the conversions of the time histories of each group since the flare time, $I(t_i-t_o)$, to path length distributions,

$I(x_i)$, using the average velocity of each differential group to make each appropriate conversion. The first interpretation inferred from this result is that all energy populations travel a given path length (before propagating to 1 a.u. radial distance) with the same probability, so that the scattering has a velocity independent mean free path. In addition, these curves also happen to be fits to the simple diffusion equation through the region of maximum intensity, as one can separately verify by plotting $\ln(I \cdot t^{1.5})$ against $(-t^{-1.})$. Another direct result is that all onsets are considerably delayed, characterized by a path length which is several times greater than the direct distance from the sun to the earth, and accompanied by a most probable path length which is an order of magnitude greater than that distance. One therefore infers that either there is a remarkable interplanetary diffusion or that there is considerable storage of the particles near the sun. Yet another inference results from noting that since all the curves have the same shape, a scaling normalization (such as that at peak intensity, or the total count rates representing the areas under the curves) can be used to provide an absolute differential spectrum of this particular event. It is, of course, tempting to identify this absolute spectrum with the source spectrum at the point of release. The question of the validity of this identification is not at present resolved, because of the question of the apparent velocity independent propagation, as compared with the strong velocity and rigidity dependence of the modulation of galactic cosmic rays of similar energies by the solar environment. Finally, it is interesting to note that the absolute spectrum is perfectly represented over a wide dynamic range by a power law in kinetic energy, as shown in Figure 3, which also includes an additional example of such an event in 1962. Related questions, such as the nature of the propagation medium and the locations of the trapping region, of the point of release of the accelerated particles, and of the detector location relative to the solar longitude of the event, all have to do with the interpretation of the absolute spectrum as the source spectrum. For example, the November 10, 1961 event, shown in Figure 4, has by contrast propagation curves that differ as a function of energy or velocity over a more limited dynamic range.(2) This one was from a 90°W flare, whereas the prototype came from one at 30°E. Thus, either this longitude difference, or perhaps the conditions existing in the near-solar or interplanetary environments may have caused the failure of this event to conform to a unique path length distribution. Perfect velocity independence is clearly not always found.

The other categories of events include the storm particle events, which occur with much steeper spectra, being composed of mostly low-energy protons detected at a few MeV.(3) Such events occur in coincidence with geomagnetic disturbances and Forbush decreases of high-energy cosmic rays; they have essentially no velocity dispersion. Their properties may be more related to interplanetary parameters than to original conditions at the sun.

Events of the third category, namely, the recurrent events, were first found to originate directly after flares with the September 1961 sequence previously shown, and with another such sequence in later 1961.(4)

Later on, similar corotation events were found to be present, but without any identification to parent flares. Figure 5 shows a series of 27-day repeating events which persisted not only throughout mid-1963, during the lifetime of the Explorer XIV instrumentation[5], but continued until at least January 28, 1964.[6] There was no obvious way to connect this series to visible-disk flares, but, of course, considering the occasional rejuvenization, one might speculate about activity on the back of the sun. Both the flare correlated recurrence events and the long-lived series of flare-independent events are accompanied by recurrent Forbush decreases and geomagnetic activity. All such events are characterized by the lack of velocity dispersion and by exponential energy spectra, such as those shown in Figure 6, in contrast to the power law spectra which can characterize direct flare events.

With the onset of new solar activity following 1964, low-energy proton increases became more frequent and less obviously well ordered in their times of occurrence than was evidenced by the first, elegantly simple series. As solar maximum is approached, as shown in Figure 7, a large number of medium energy proton events appear.[5] At low energy, the frequency of proton (and of electron) events increases to the point that minimizes the existence of any genuinely quiet times, as is evident in Figure 8.[6] Even in the quietest available periods, when the low-energy intensity is at a minimum, the interplanetary differential proton spectrum contains a separate component in the <20 MeV region. J. Kinsey in his doctoral thesis investigated the possible galactic origin of this low-energy component.[7] He studied 4-day averages of the 4 to 80 MeV proton spectra during the interval May 1967 to August 1968 with the working assumption that each spectrum in this interval is composed of two power laws. All his results are consistent with the picture of a low-energy component of varying intensity (decreasing with increasing energy) and of solar origin, connecting to an approximately constant higher-energy galactic component (increasing with increasing energy). The minimum or valley in any observed spectrum is merely a function of the solar component intensity at the time of observation.[8] The conclusion is, therefore, that, during this part of the solar cycle at least, the sun must be viewed as a continuous source of few-MeV protons.

The phenomenology of the frequently occurring low-energy proton events at times nearer the solar cycle maximum bears further examination. Throughout several years, the intensities of interplanetary flare events are found to vary over a wide range of magnitude, but all those related to flares account for only a fraction of the total number of events at low energies. Corotation events are found in abundance, and the temptation to associate many of these with active centers on the sun found some success, first with the events detected with Simpson's Pioneer experiments[9], and later with the studies of IMP results by Kinsey.[7] Figure 9 shows his association of events with central meridian passage of calcium plage regions, in which the regions are numbered and, if recurring, connected horizontally. It is appropriate to comment that a two-stage acceleration mechanism, approximately as postulated by Schatzmann,[10] was suggested by Fichtel and McDonald[11] as accounting for the phenomenology of these events: A somewhat steady-state storage over weeks or months of low energy, few-MeV protons occurs above an active center, followed by a second stage of energy increase in the flare release. A verification of this picture, such as the observation of a charge composition in corotation events similar to that in flare events, has not been accomplished. Another possibility is that a preliminary particle acceleration much closer to the time of a flare may occur; that is, particles may undergo an initial increase in energy and then remain stored for a few hours prior to the final acceleration at the flare time. The March 24, 1966 and January 28, 1967 events, shown in Figure 10, hint at this possibility, each having a precursor of soft protons for a few hours before the main event. The March 24 flare took place on the visible disk and was accompanied, after the precursor, by a hard (>180 keV) X-ray event observed with the OGO-I.[12] The January event had X-ray coverage from OGO-III only for a limited time which should have been sufficient to include the X-ray burst time, except that the event is, however, assumed to be from a back-side flare. It is accompanied by a considerably lengthy precursor, and may therefore be quite similar to the March event. It is possible, of course, that these data do not necessarily require the existence of a multi-stage acceleration, but may result simply from the occurrences of small and large events in rapid, independent sequence.

The phenomenology of solar particle events can be continued with the following mention of results concerning solar electron events. The first solar-flare electrons of relativistic energies observed directly in interplanetary space were those from the July 7, 1966 event. Their time history is shown in Figure 11a, compared with those of several groups of medium-energy protons. The considerably earlier onset of the electrons, some two hours before the protons, is evident. These electron and proton data are shown in Figure 11b, having been converted to path length distributions.[13] All the curves have a common fit, similar to the case for those of the September 28, 1961 prototype. Again, the conversion is determined by the zero of time, which was set, to allow for travel time, at 500 seconds before the X-ray burst time. The remarkable, additional fact here is that 3-MeV electrons have even much lower rigidities than did the lowest energy protons observed in previous events which were found to conform to velocity independence of path length distributions. The propagation is the same for these few-MV rigidity electrons as for energetic protons, indicating that the trapping, storage and escape parameters are each rigidity and energy independent over several decades. As Anderson and Lin have shown, this universality finally breaks down for the 40-keV electrons.[14] Also, as shown in Figure 12, the propagation curve for the electrons fits the standard diffusion curve through maximum intensity, as evidenced by the direct proportionality between $\ln(It^{1.5})$ and $(-t^{-1.})$ which continues until late in the event. The diffusive nature of the several-MeV electron events, like that of high-energy proton events, appears to be often the case; several examples of such events are shown in Figure 13. Here, four series of tests for diffusion (for the events of July 7 and September 14, 1966, and February 27 and March 11, 1967) are plotted, in which the zero of time is varied by 500 seconds from plot to plot. In each of the four cases, the best linear fit is empirically found to occur at the time which happens to match the time, at the sun, of microwave and/or hard X-ray intensity maximum. One possible inference is therefore that the interplanetary electron population is a direct sample of the electron population which causes the microwave and hard X-ray burst, being simultaneously injected into the diffusive medium. Other inferences have been made using the data from the July 7, 1966 event: first, the total number of interplanetary relativistic electrons is far greater than the total number of interplanetary relativistic protons emitted, as estimated either from using the intercepts on diffusion plots, or simply from the differential intensities observed. Correspondingly, it was a very intense event in both microwaves and in hard X-rays. Also, the total number of electrons detected allows for some estimate of the total number emitted into interplanetary space; comparison with estimates of the electron population at the flare site inferred from the X-ray data indicate that the electron population released into interplanetary space is a small fraction, perhaps a few percent, of the electron population responsible for the hard X-rays.[13,15] Studies of the electron to proton ratio in solar events as a function of velocity or energy have not yet been systematically carried out, but may eventually indicate a correlation to the X-ray characteristics.

The subject of the other categories of electron events can be introduced by the plot, shown in Figure 14, of the relativistic electron daily intensities from autumn 1963 to spring 1969, with a one-year gap from mid-1964 to mid-1965.[16] The flare events, marked with dark bars, are typically off scale, and we are left with the remaining maze of quiet time activity perhaps analogous to the low energy proton picture. A plot of the same data, but with the larger flare events removed and the remaining daily averages smoothed by four-day running averages, is shown in Figure 15. A variety of time variations, including such features as the 27-day corotation events in late 1967, is brought out. The question similar to that asked in the Kinsey investigation of low energy protons is, of course, that of the possible solar origin of all these electrons. One difference between this situation for the electrons and that investigated for the protons is that there appears to be an envelope of minimum electron intensity which is constant, to within better than a factor of two, over all five years. Given the fact that all of the quiet-time intensity increases have the same differential energy index as the minimum or background envelope, which is only -2 to -3 (and definitely not the same as either the flare index, which is -4 to -5, or the storm electron event index, which is steeper) one infers that the quiet-time increases are most simply assumed to have the same origin as the quiet-time minimum envelope.

The question of the origin of this interplanetary background can be deferred with an inquiry into the phenomenology of these many increases. In general, it is found that the picture of the shock or storm events which frequently occur at much lower energies, for example, $\approx$40 keV, is quite different(17,18); but those events are generally too steep to be observed at several MeV. The quiet-time MeV increases are much flatter in spectral slope, as stated above, and do tend to display an interesting intensity pattern. Figure 16 shows a portion of the same data again, in which some of the more obvious quiet-time electron increases are indicated with the shaded bars. During other periods of time, the decreases or intensity minima are more obvious in appearance, and are marked with downwards arrows. In Figure 17, the low energy, several-MeV, proton history for about a year is shown[16], in which the electron intensity maxima, shown by the shaded bars, appear to be at the times of proton intensity minima, and the electron intensity minima, shown by the downwards arrows, occur at various proton intensity maxima. This property of quiet-time electron intensity increases (anticorrelated or at least out of phase with the low-energy proton intensity increases) was first noticed with our 27-day spaced IMP-I series[19], but at that time could only be dismissed as one randomly phased recurrence series. It now appears, as we get halfway into the solar cycle, that this anti-correlation is a fundamental, or at least a very persistent, property of the quiet-time interplanetary electron population. It is as though the sun emitted low rigidity electrons and protons in beams 180 degrees apart. Of course, the effect may, instead, have to do with the solar modulation of galactic electrons. Perhaps this effect is analogous to the early picture of the earth's trapped radiation, which seemed to be composed of two zones, the inner, proton, and the outer, electron, which picture eventually was resolved as one continuous physical distribution. We have yet to scrutinize the array of data necessary to resolve the corresponding total picture of quiet-time interplanetary electrons.

Another quite different topic in particle production is the interesting flare-time event series of July 1968. This series of electron and proton events has features which preclude its easy categorization and have brought forth some novel interpretations. Figure 18 shows the histories of 11 to 100-MeV protons, and 300 to 900-keV electrons during the period of July 6 to 16, 1968.[20] Flare electrons and protons followed the X-ray burst on July 6, but there was no new particle increase following a second X-ray burst on July 8. Following and possibly associated with one small flare event on the 9th and two on the 12th of July, there were again particle increases, but it is the increase on the 13th that causes the controversy. Simnett has conjectured that the electron event of the 13th was due to a disturbance (possibly related to the flare of 1341 UT on the 12th) which triggered the release of particles which had been stored near the sun since the intense microwave and X-ray events of the 6th or 8th.[20,21] This picture is consistent with the following: (a) the two events which took place after July 8 were below the limit of X-ray detectability as shown in Figure 19 (except that the one of 1341 UT on the 12th had no hard X-ray coverage); (b) the microwave spectra for these three events are also less intense than for those of the 6th and 8th; and (c) the two events on the 12th have radio spectra which, unlike microwave bursts, increase towards the lower frequencies. All these results are consistent with a minimum likelihood of the association of the events of July 9 to 12 with electron acceleration. Contradicting this picture of storage for at least five days is the interpretation that the event starting near noon on the 12th is a new flare event, and that the event of noon on the 13th is a shock or storm particle event.(21) This picture is also consistent with the appearance of a geomagnetic disturbance on July 13.

The next topic to be briefly mentioned is that of elementary particle production in flares. The possibilities of meson (and consequently positron) and of neutron production in flares have been discussed by a number of authors, in particular, Ramaty and Lingenfelter.(22) To date no experiments have had the sensitivity to detect directly interplanetary populations of such flare particles, or to obtain indirect evidence of their production at the sun. Three such searches I have made can be quickly outlined. First, instruments sensitive to interplanetary positrons of a few hundred keV to 2 MeV were flown on two OGO satellites. The detection efficiency of each was low, due to the probability of observing the converted annihilation quanta in the coincident gamma-ray spectrometers. Electron events, such as that of July 7, 1966, have been examined, and upper limits to the positron to electron ratio in the $\approx$1-MeV population have been set at a few percent.(12) This result is not sufficiently restrictive to make possible the adoption or elimination of a relevant theoretical model of elementary particle production. Second, the X-ray spectrum of flare bursts such as the same July 7, 1966 event observed with the same instrument on OGO-III, shown in Figure 20, were examined for the existence of the 0.51-MeV line.(24) The periods following the X-ray bursts were also examined for the annihilation quanta of positrons which take considerably delay in coming to rest in the solar atmosphere. All these searches have all been fruitless and result in similarly weak upper limits on the positron production intensities in flares. Most probably, cryogenically-cooled, low-background gamma-ray detectors will be necessary to resolve the 0.51-MeV line in such events. Third, a charged particle detector flown on OGO-V incorporating the dE versus E technique was used to look for solar flare neutrons. Downwards travelling protons and electrons which stop in the detector were separated from knock-on protons created by neutrons within the material of the detector by examination of the coincident energy loss and residual energy deposited by each particle. This technique was used to search for flare neutrons between the time of the X-ray burst and the time of arrival of the solar protons for several large events during late 1968 and early 1969. This may have been the highest sensitivity solar neutron search, since both the predicted times of arrival of neutrons and the predicted range of knock-on proton energy for the maximum neutron intensity were matched in this interplanetary study. Nevertheless, no evidence for any additional counting rate over cosmic-ray background was found, that is, no increase above the several background counts per hour.(12) The absolute upper limits on neutron production have not yet been published for these events.

The last topic I wish to outline is that of energetic solar X-rays related to the electron and proton flare events such as those discussed here. Over the last decade, a number of observers have been able to study the energetic X-ray emissions from large solar flares. In addition, the studies of the radio emissions at the flare times have been more sophisticated, and detailed comparisons have recently become possible. Figure 21 shows the dynamic radio spectrum of the July 7, 1966 event, in which the frequency is plotted vertically and the time horizontally.[25] The flux density is indicated by the darkness of the shading. Microwave emissions have peaks early in the event at 0027 and at 0029, and again, at maximum intensity, at 0037 UT. The lower frequency emissions are at maximum intensity an hour or so later. In Figure 22, the very high frequency microwave flux density is plotted versus time, as are the intensity of X-rays of energy above 80 keV, observed with OGO-III.[26] The similarity in time profiles is clearly seen. The integral spectrum, previously shown in Figure 22, indicates a nonthermal, or at least non-isothermal, nature. Such energetic events as this have become quite common in the recent years covering the first half of the present solar cycle; at the high energies near several hundred keV the events generally have one intense peak, with a 1/e fall time of approximately one minute. As has been known in general for some time, and recently described in detail by Kane[27], the X-ray time histories, like the microwave bursts, generally have the briefest duration at the highest energies, peaking prior to the maximum of the slower buildup at the lower energies. Figure 23 shows the soft and hard X-rays from the August 28, 1966 event. It confirms this general picture, indicating a short burst at an early time for the >80-keV component and a later, broad maximum several orders of magnitude above the detector background for the soft, few-keV component before the arrival of the charged particles. (Please note the fact that the OGO-III satellite was spinning when these data were recorded, causing a periodic time variation in the recorded

X-ray intensity; the smooth source time profile is, of course, formed by the maximum-intensity envelope of this curve, and any finer time variations are lost.) In contrast to single-peak X-ray events such as the July 7 and August 28, 1966 flare bursts, we examine in Figure 24 the soft X-ray component of the May 23, 1967 flare event.(12) Three independent bursts are seen at approximately one hour intervals. The first of these three is too weak to have an observable component at the high energies, but the second two are essentially as intense above 80 keV as were the July and August events discussed above. Figure 25 shows the >80 keV time histories of these two bursts; again the periodicity of the data is due to the roll modulation of the detector. In spite of the resulting poor time resolution, the complex behavior of the second hard X-ray event is seen. Noticeable also is the fact that the second event is spectrally harder, because the amplitude of the roll modulation is not as great. These time variations are yet to be fully understood.

More recently, improved time resolution, achieved with Frost's instruments on the OSO spacecraft, has made possible new advances in X-ray studies. Figure 26 shows the March 1, 1969 event, in which extremely fast variations of only a few seconds rise or fall time are seen. Also clear is the usual high energy peak, typically in advance of the slower, lower energy maximum. These fast, quasiperiodic fluctuations in the onset of the event have been suggested by Frost as being due to the repetitive production of monoenergetic electrons by instabilities in the magnetic field during the initial stage of the flare.(28) Some very recent results of his form an extremely interesting contrast to the general features of the X-ray bursts as previously understood. Figure 27 shows an event with the following new and unusual feature: the slower and more delayed intensity maximum is that of the harder or more energetic X-ray component, not the less energetic. Here the fast, initial burst is dominant at medium energies but the energies of the slow component are much higher, namely, several hundred keV.[30] Frost and Dennis suggest that this result provides evidence for a rapid, two-stage particle acceleration process, in which the first burst is considered to be bremsstrahlung from electrons accelerated to perhaps 100 keV by such a process as an induced electric field; the second represents radiation from the following stage in which the electrons are Fermi-accelerated to higher energies, possibly by an advancing shock front. This X-ray event profile may not be unique, but may be simply a member of a continuous distribution of event profiles, including single and compound peaks, such that the harder burst can be either the first or the second in the case of the double peaked events, and such that the importance of two-stage acceleration varies from event to event. Such a view of X-ray flare events lends some credibility to a single all-compassing picture of two-stage acceleration.

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FIGURE CAPTIONS

1. Interplanetary particle event series, indicating three types of events.
2. Path length distributions for the September 28, 1961 event.
3. Absolute differential spectra of two flare events.
4. Path length distributions for the November 10, 1961 event.
5. Long-lived interplanetary event series.
6. Differential energy spectra of recurrent events.
7. History of the intensity of medium energy interplanetary protons.
8. Histories of low energy protons and of low energy electrons.
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10. Proton flare events possessing precursors.
11. Intensity histories and path length distributions of flare particles from the July 7, 1966 event.
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15. Four-day running average study of the electron history of Figure 14.
16. Low energy proton history indicating electron maxima (bars) and selected proton maxima (arrows).
17. Low energy electron history indicating the same data as in Figure 16.
18. Time histories of very low energy electrons and medium energy protons for the July 6 to 16, 1968 event series.
19. Hard X-ray events or their absence for the flare events of the July 6 to 16, 1968 series.
20. Integral X-ray spectrum of the July 7, 1966 flare event.
21. Dynamic radio spectrum of the July 7, 1966 flare event.

22. Comparison of hard X-rays and microwaves for the July 7, 1966 event.

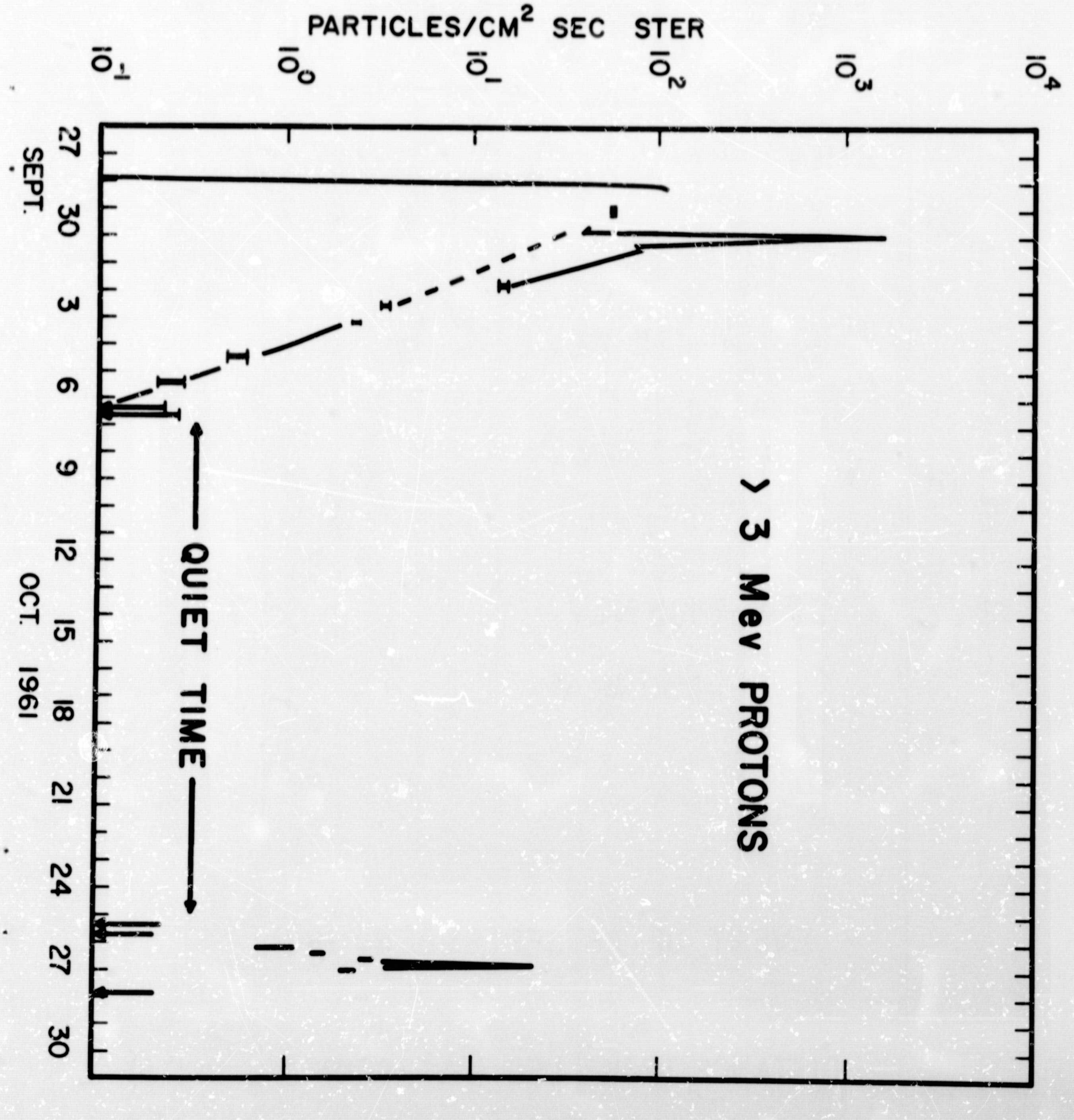
23. Time history of soft and of hard X-rays and charged flare particles for the August 28, 1966 event.

24. Time history of soft X-rays for the May 23, 1967 event.

25. Time history of hard X-rays for the May 23, 1967 event.

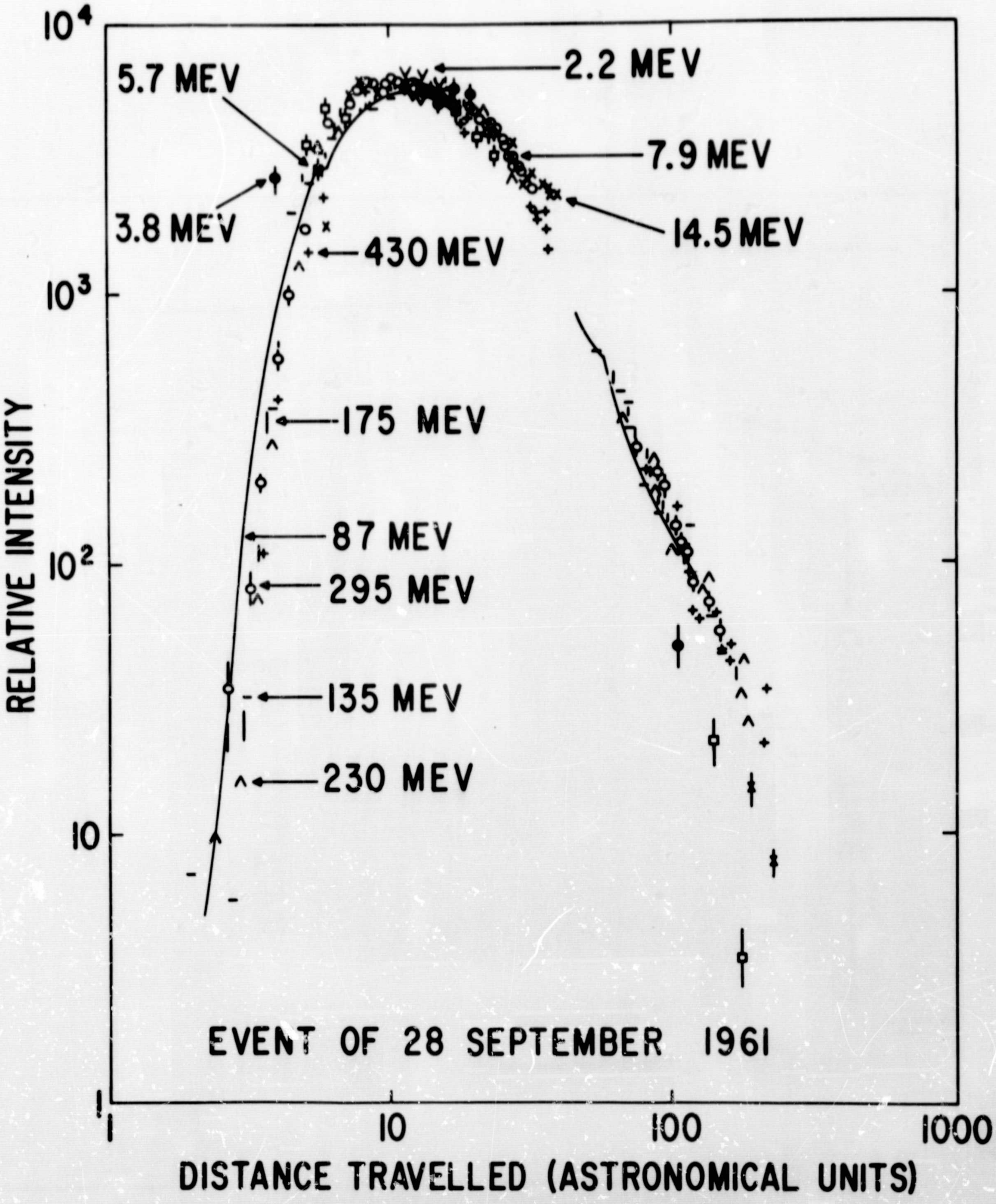
26. Comparisons between X-ray and radio time histories for the March 1, 1969 flare.

27. Time histories of flare X-rays for the March 30, 1969 event.



PARTICLES/CM² SEC STER
10⁻¹
10⁰
10¹
10²
10³
10⁴
> 3 Mev PROTONS
QUIET TIME
27
30
3
6
9
12
15
18
21
24
27
30
SEPT.
OCT. 1961

Figure 1



2.2 MEV
5.7 MEV
7.9 MEV
3.8 MEV
14.5 MEV
430 MEV
175 MEV
87 MEV
295 MEV
135 MEV
230 MEV
EVENT OF 28 SEPTEMBER 1961
RELATIVE INTENSITY
DISTANCE TRAVELLED (ASTRONOMICAL UNITS)
10⁴
10³
10²
10
1
1
10
100
1000

Figure 2

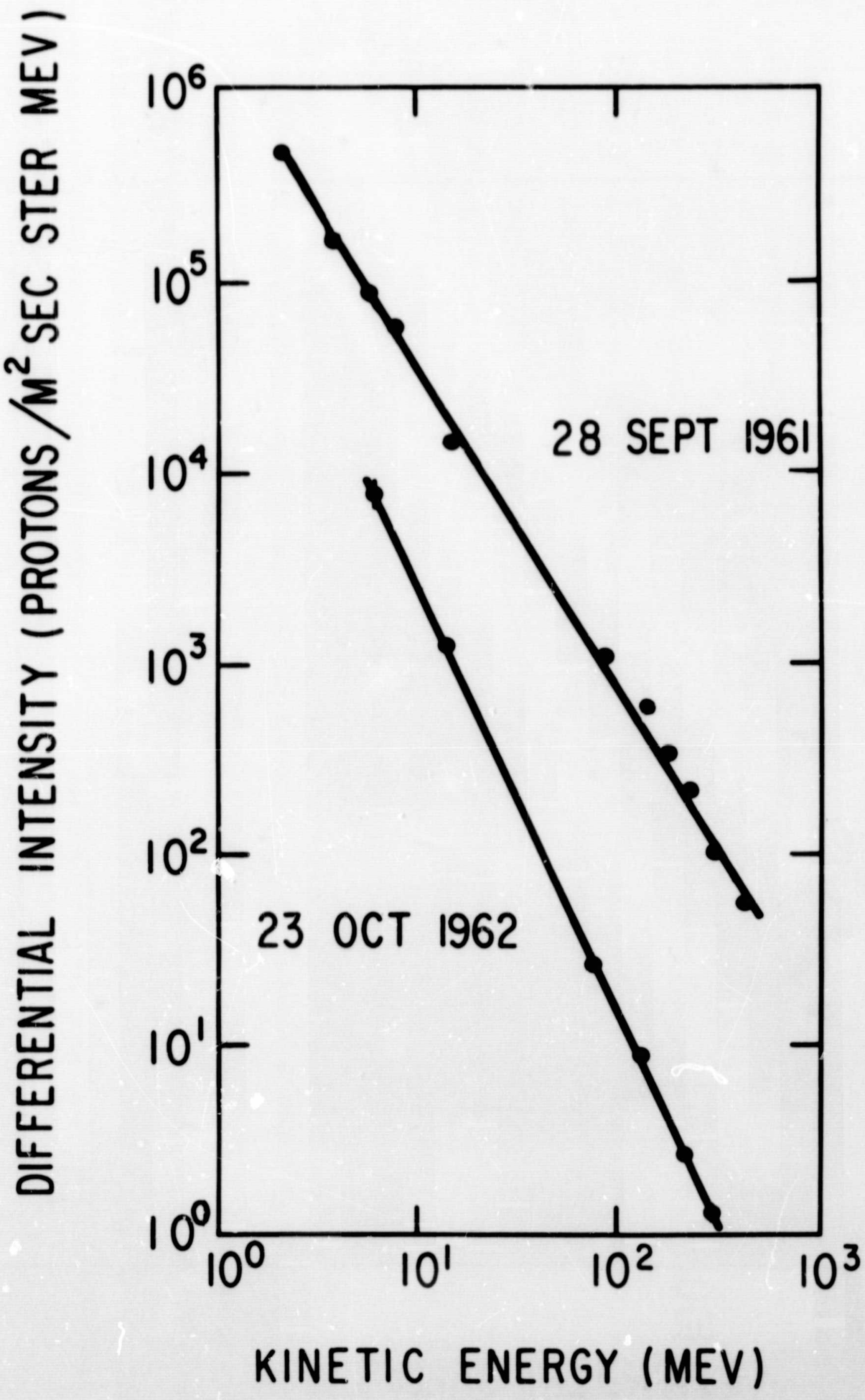

DIFFERENTIAL INTENSITY (PROTONS/M² SEC STER MEV)
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
28 SEPT 1961
23 OCT 1962
10⁰
10¹
10²
10³
KINETIC ENERGY (MEV)

Figure 3

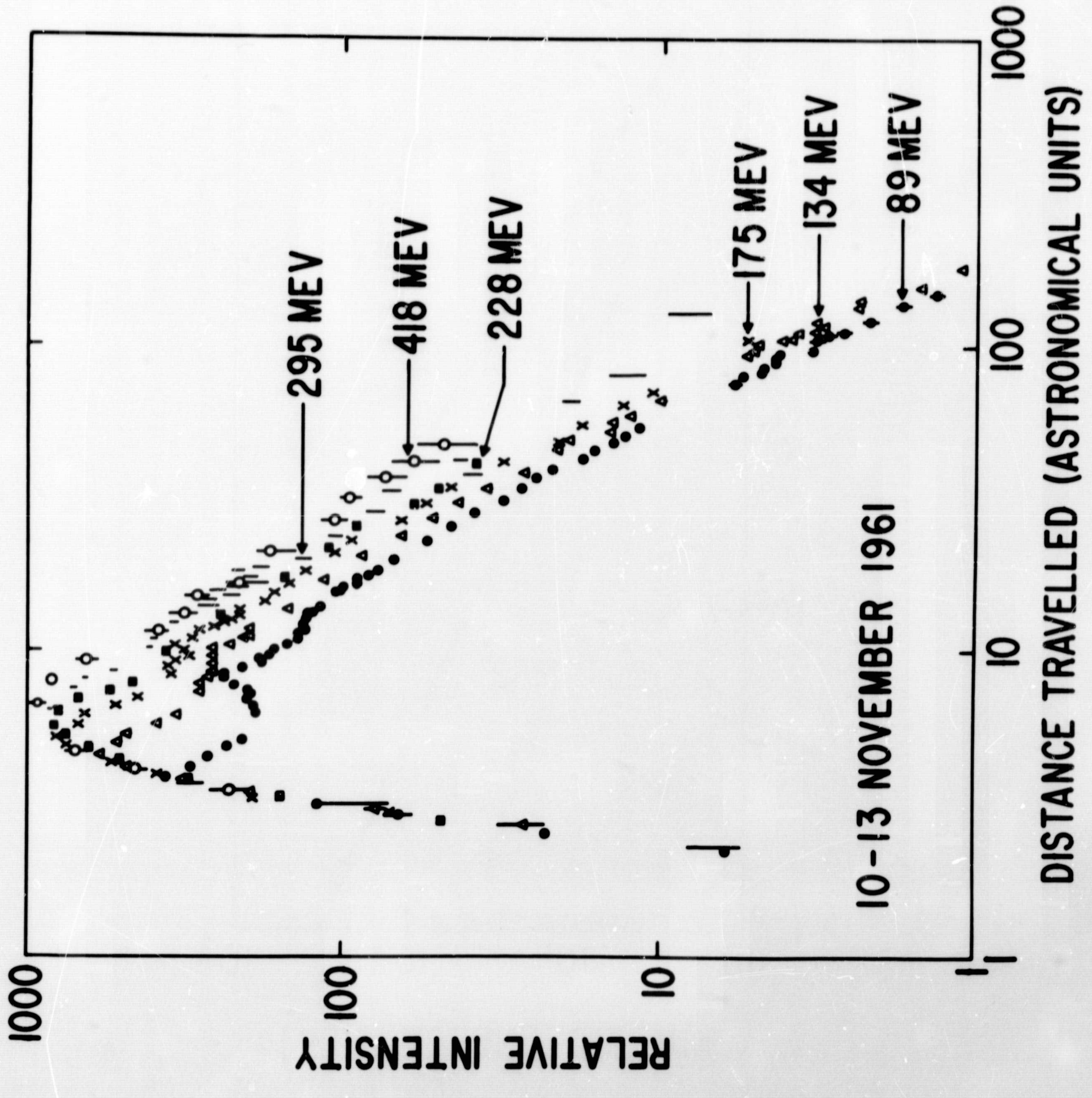

295 MEV
418 MEV
228 MEV
175 MEV
134 MEV
89 MEV
10-13 NOVEMBER 1961
RELATIVE INTENSITY
1000
100
10
1
10
100
1000
DISTANCE TRAVELLED (ASTRONOMICAL UNITS)

Figure 4

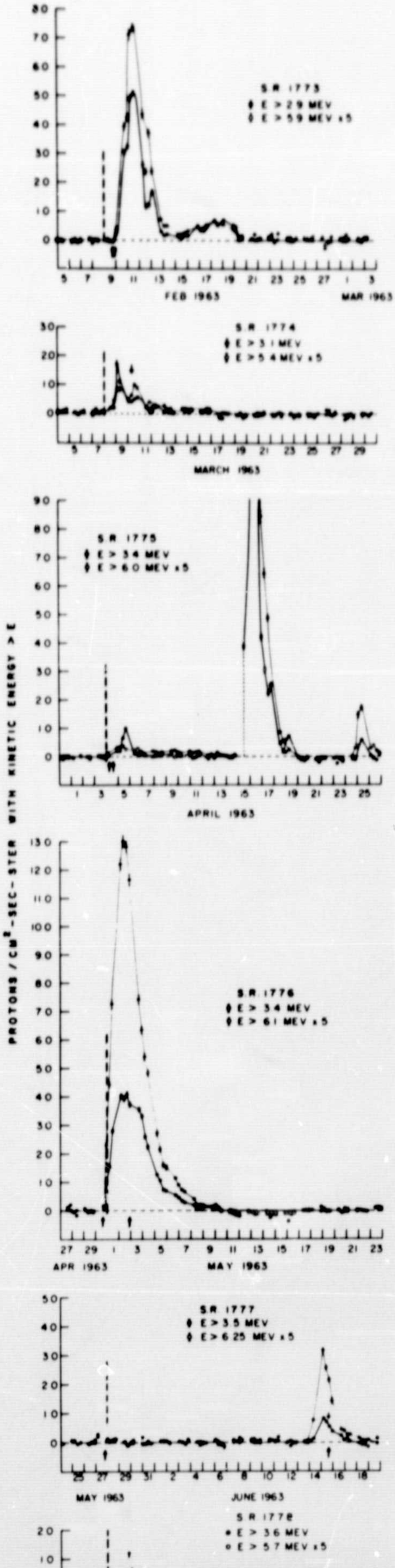
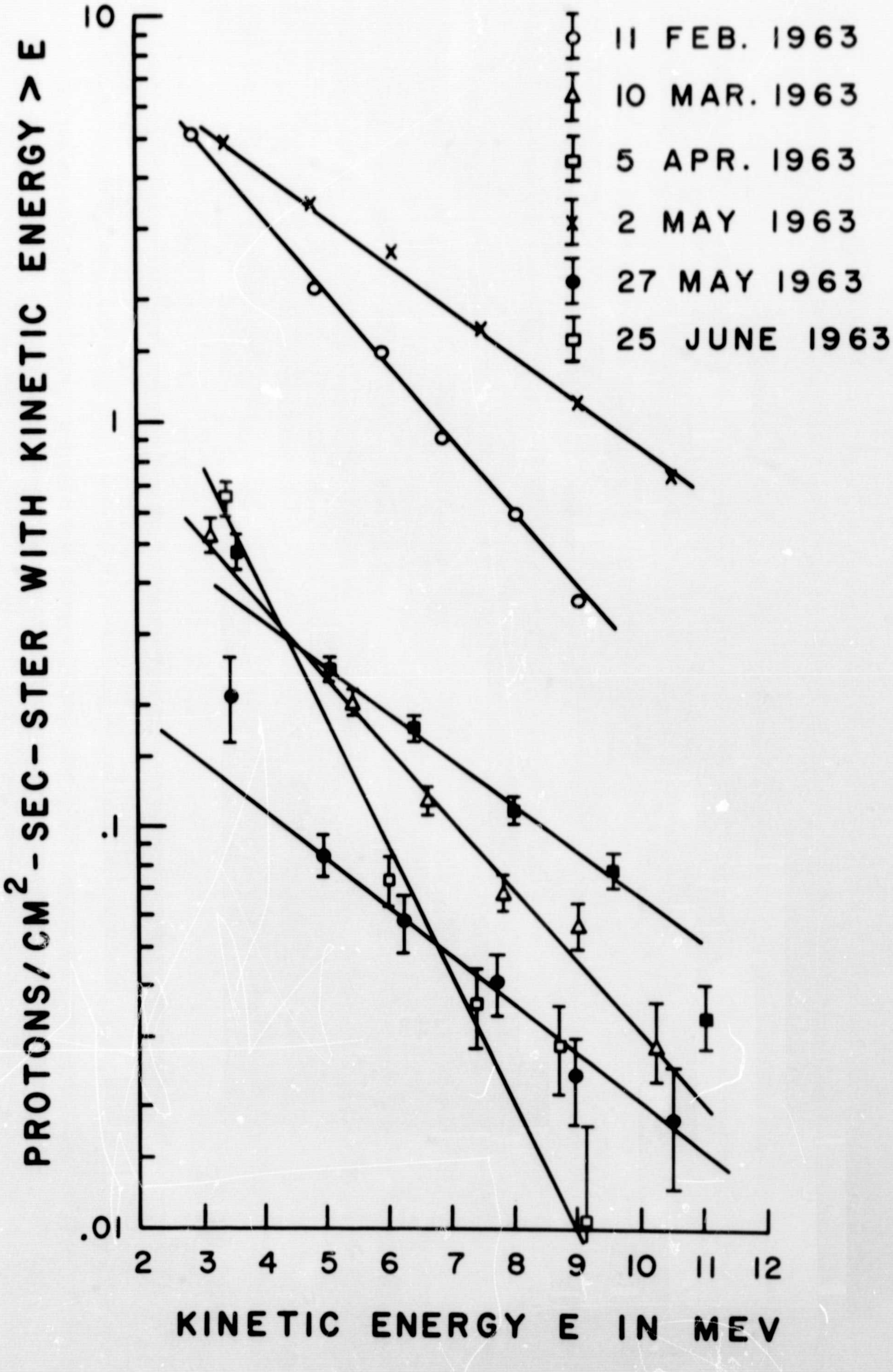

PROTONS / CM² - SEC - STER WITH KINETIC ENERGY > E
S.R. 1773
E > 2.9 MEV
E > 5.9 MEV x 5
FEB 1963
MAR 1963
S.R. 1774
E > 3.1 MEV
E > 5.4 MEV x 5
MARCH 1963
S.R. 1775
E > 3.4 MEV
E > 6.0 MEV x 5
APRIL 1963
S.R. 1776
E > 3.4 MEV
E > 6.1 MEV x 5
APR 1963
MAY 1963
S.R. 1777
E > 3.5 MEV
E > 6.25 MEV x 5
MAY 1963
JUNE 1963
S.R. 1778
E > 3.6 MEV
E > 5.7 MEV x 5
JUNE 1963
JULY 1963

Figure 5



11 FEB. 1963
10 MAR. 1963
5 APR. 1963
2 MAY 1963
27 MAY 1963
25 JUNE 1963
PROTONS/CM^2-SEC-STER WITH KINETIC ENERGY > E
10
1
.1
.01
2
3
4
5
6
7
8
9
10
11
12
KINETIC ENERGY E IN MEV

Figure 6

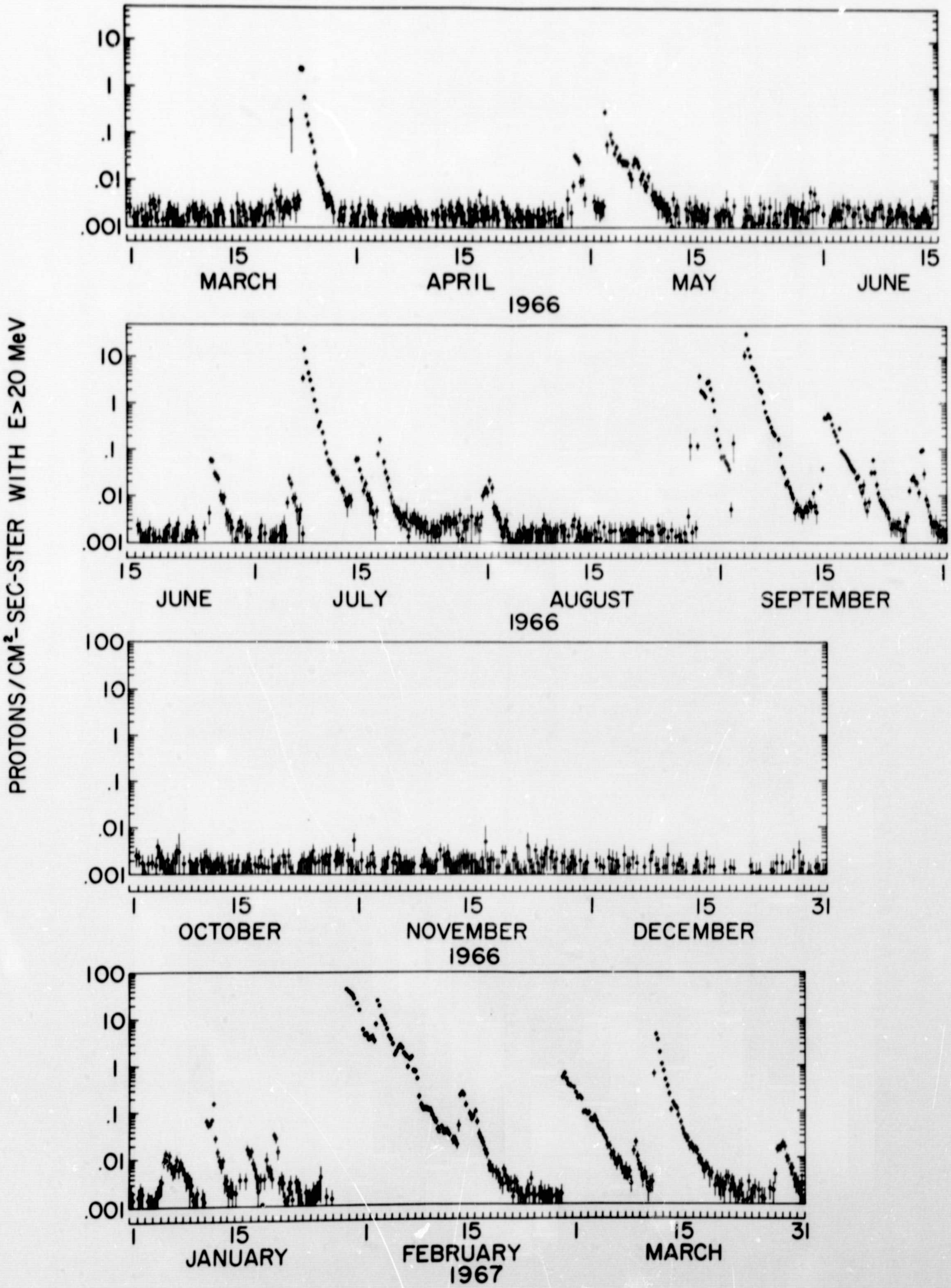

PROTONS/CM²-SEC-STER WITH E>20 MeV
MARCH
APRIL
MAY
JUNE
1966
JUNE
JULY
AUGUST
SEPTEMBER
1966
OCTOBER
NOVEMBER
DECEMBER
1966
JANUARY
FEBRUARY
MARCH
1967

Figure 7

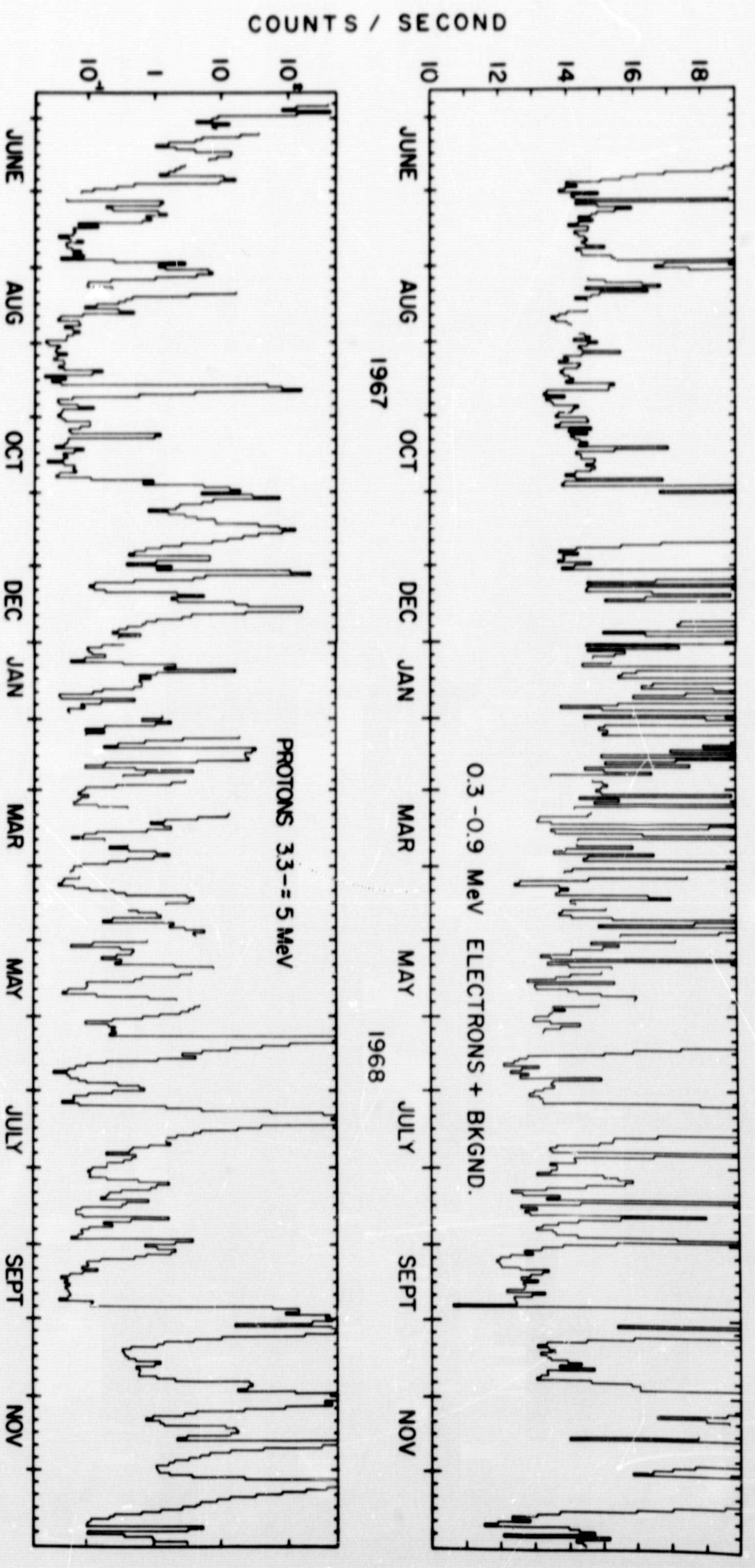

COUNTS / SECOND
10
12
14
16
18
0.3-0.9 MeV ELECTRONS + BKGND.
10^{-1}
1
10
10^{2}
PROTONS 3.3-= 5 MeV
JUNE
AUG
OCT
DEC
JAN
MAR
MAY
JULY
SEPT
NOV
1967
1968

Figure 8

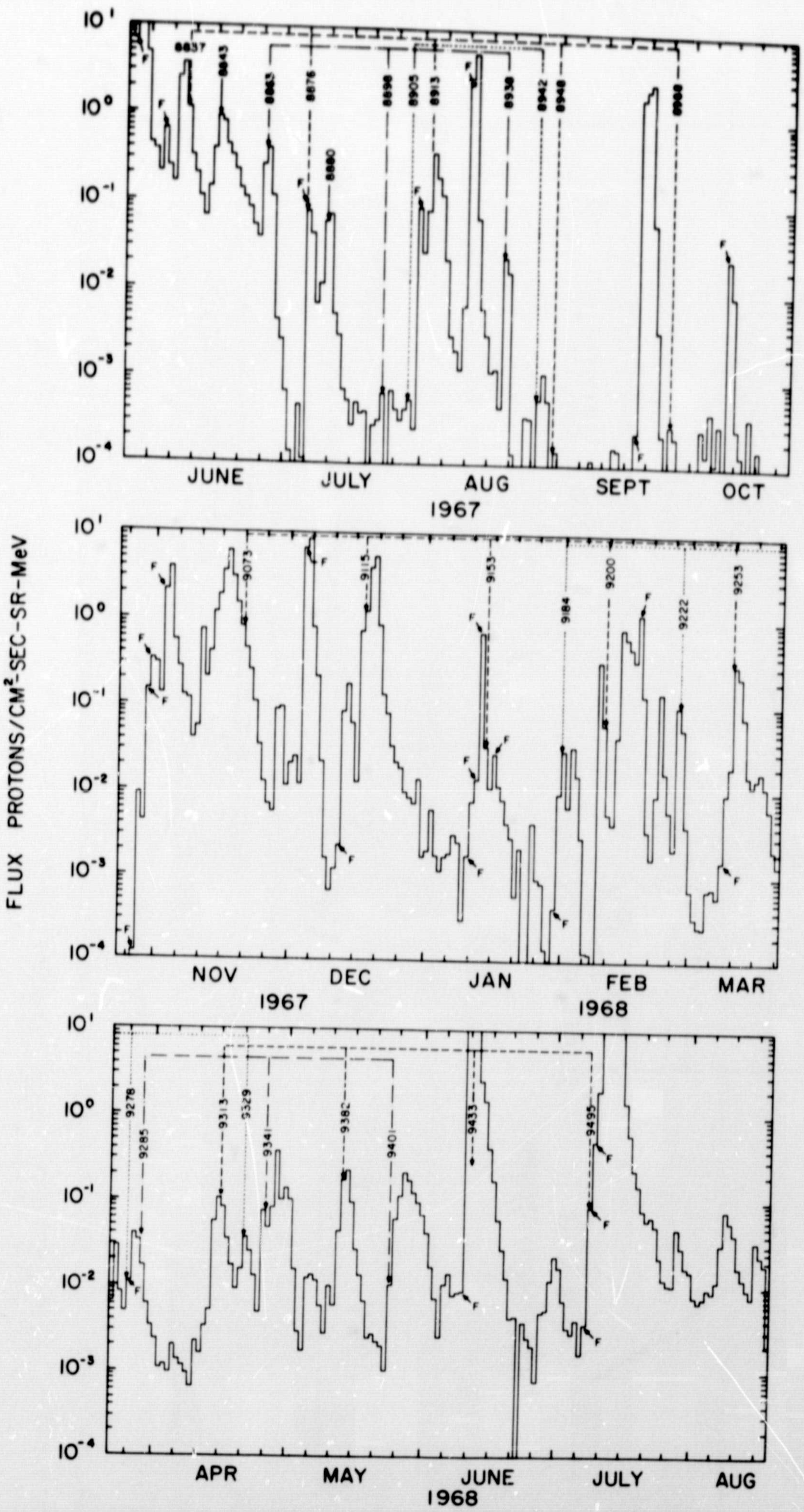
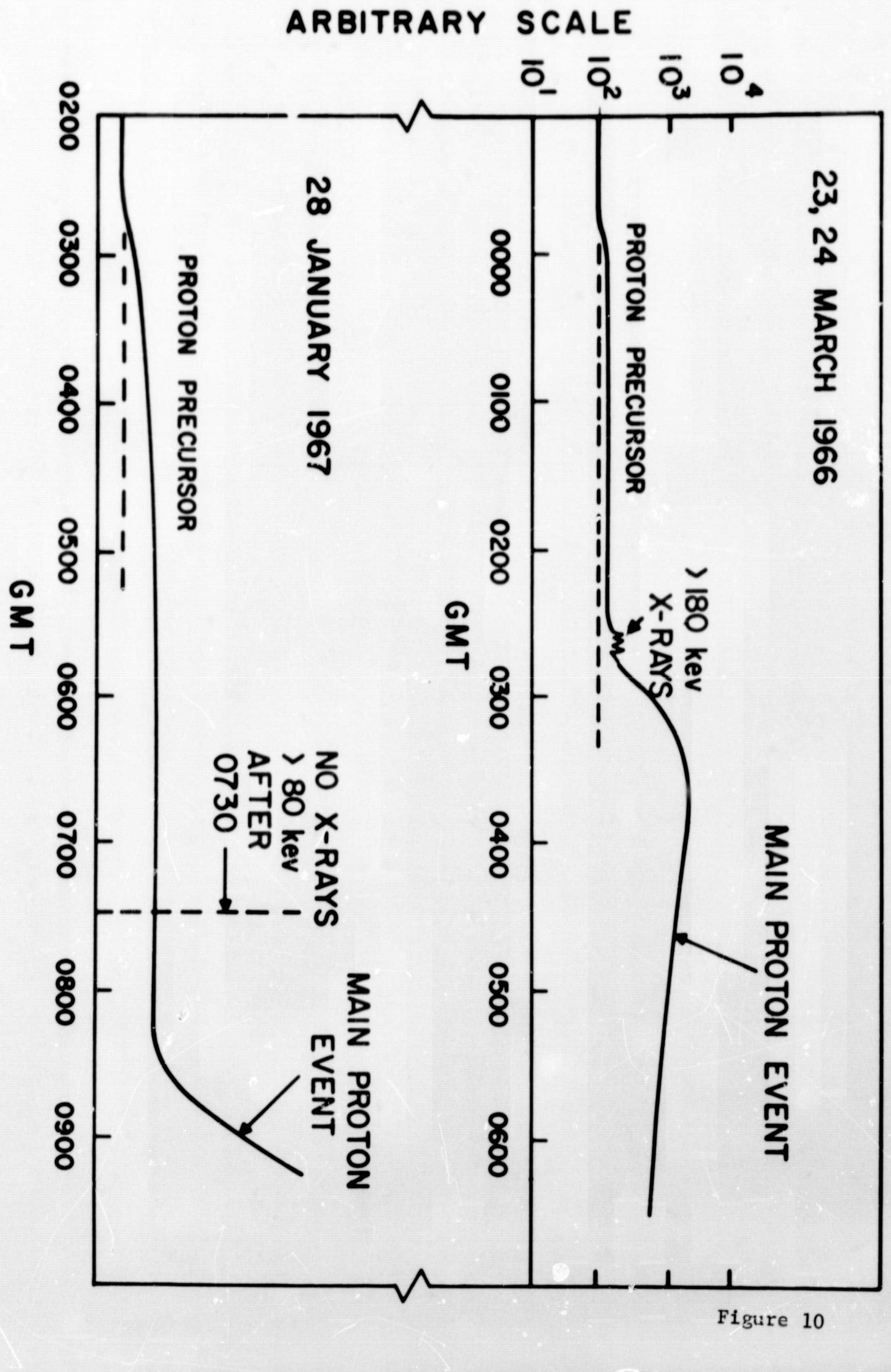

FLUX PROTONS/CM²-SEC-SR-MeV
JUNE
JULY
AUG
SEPT
OCT
1967
NOV
DEC
JAN
FEB
MAR
1967
1968
APR
MAY
JUNE
JULY
AUG
1968

Figure 9



ARBITRARY SCALE
10^1
10^2
10^3
10^4
23, 24 MARCH 1966
PROTON PRECURSOR
> 180 kev
X-RAYS
MAIN PROTON EVENT
0000
0100
0200
0300
0400
0500
0600
GMT
28 JANUARY 1967
PROTON PRECURSOR
NO X-RAYS
> 80 kev
AFTER
0730
MAIN PROTON
EVENT
0200
0300
0400
0500
0600
0700
0800
0900
GMT

Figure 10

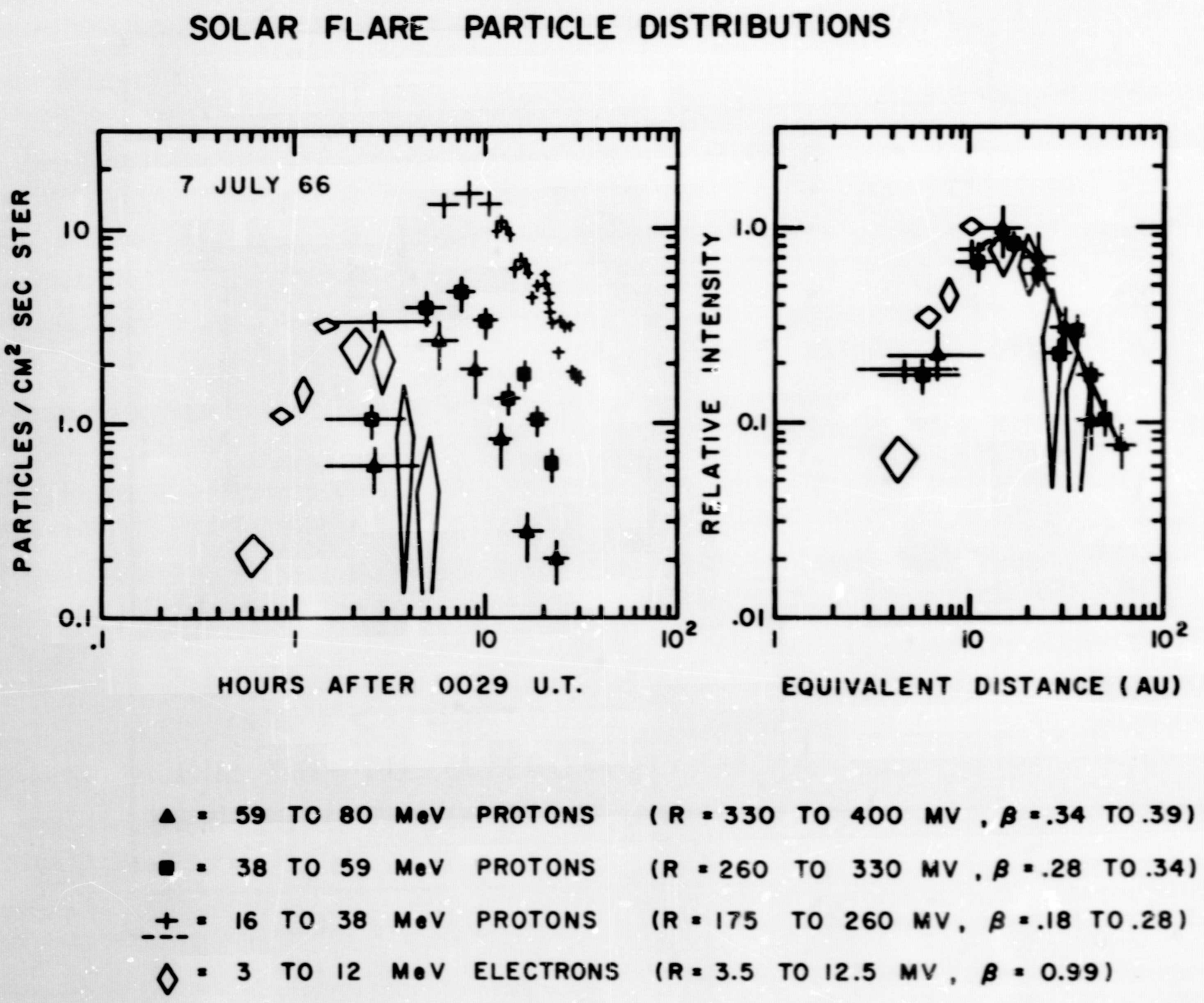
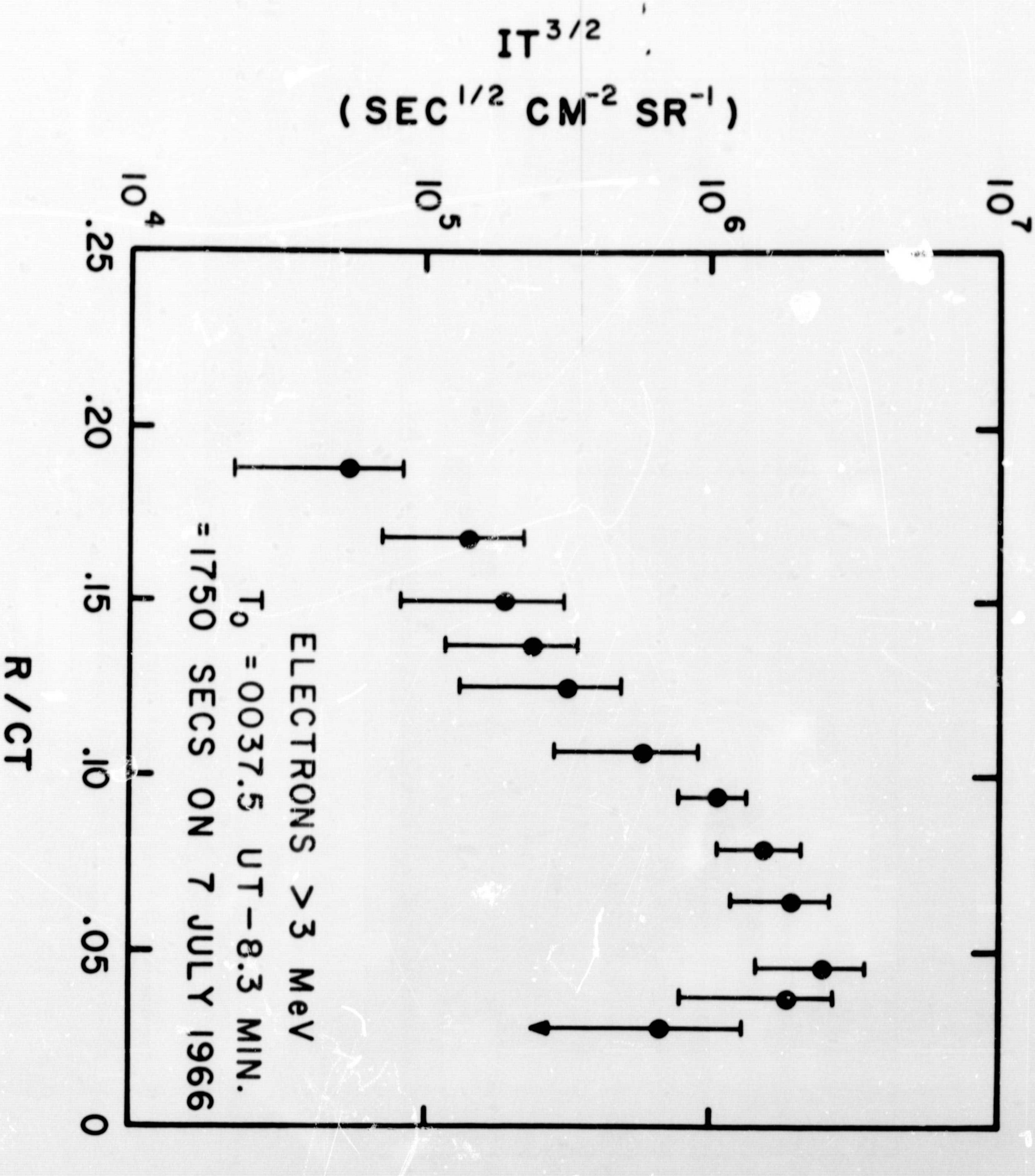

SOLAR FLARE PARTICLE DISTRIBUTIONS
7 JULY 66
PARTICLES / CM² SEC STER
10
1.0
0.1
.1
1
10
10²
HOURS AFTER 0029 U.T.
RELATIVE INTENSITY
1.0
0.1
.01
1
10
10²
EQUIVALENT DISTANCE (AU)
▲ = 59 TO 80 MeV PROTONS (R = 330 TO 400 MV, β = .34 TO .39)
■ = 38 TO 59 MeV PROTONS (R = 260 TO 330 MV, β = .28 TO .34)
+ = 16 TO 38 MeV PROTONS (R = 175 TO 260 MV, β = .18 TO .28)
◇ = 3 TO 12 MeV ELECTRONS (R = 3.5 TO 12.5 MV, β = 0.99)

Figure 11



IT3/2
(SEC1/2 CM-2 SR-1)
104
105
106
107
.25
.20
.15
.10
.05
0
ELECTRONS >3 MeV
To =0037.5 UT-8.3 MIN.
=1750 SECS ON 7 JULY 1966
R/CT

Figure 12

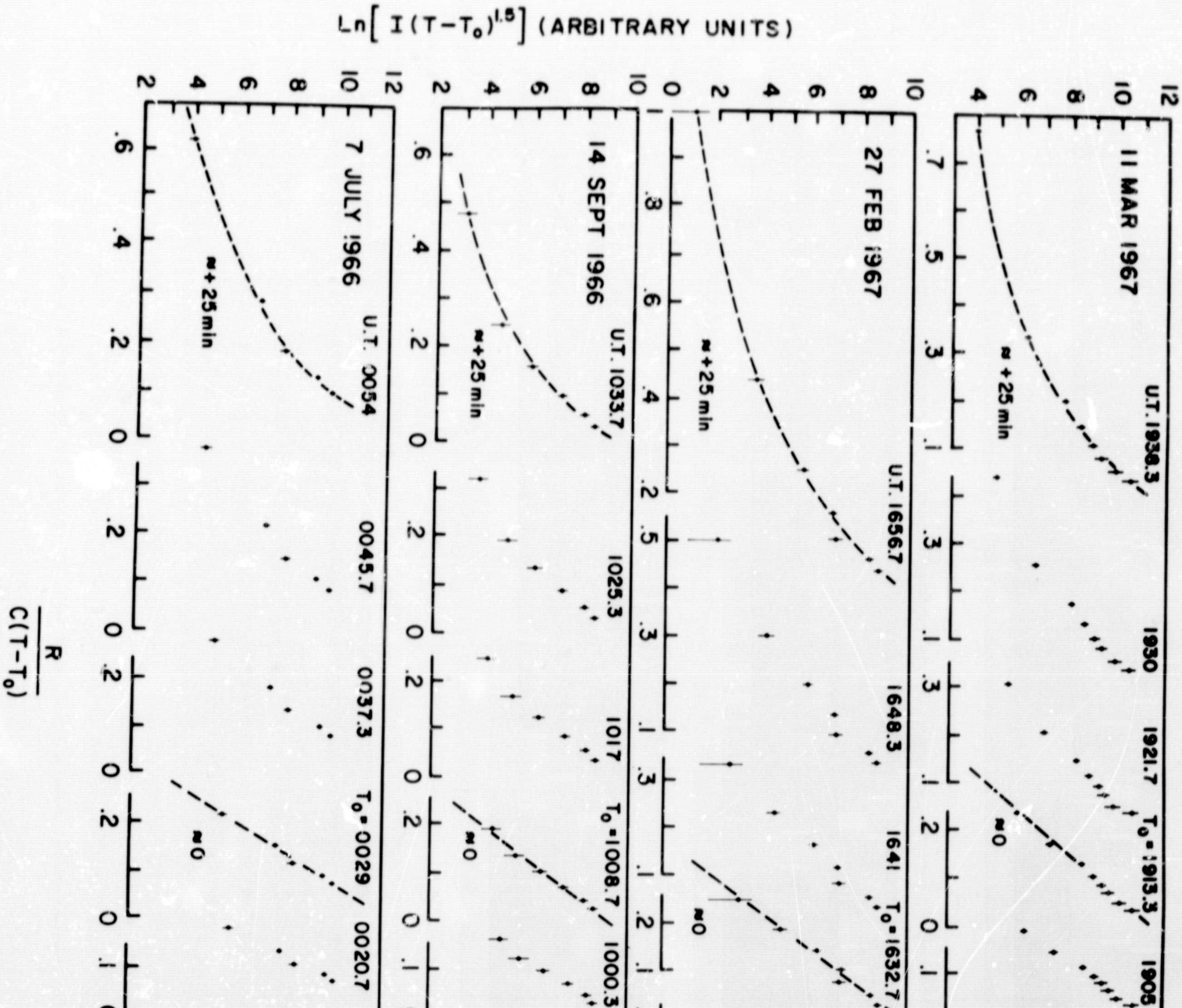

Ln[I(T−T0)1.5] (ARBITRARY UNITS)
11 MAR 1967
27 FEB 1967
14 SEPT 1966
7 JULY 1966
U.T. 1938.3
U.T. 1656.7
U.T. 1033.7
U.T. 0054
≈+25 min
≈0
≈−25 min
R
C(T−T0)

Figure 13

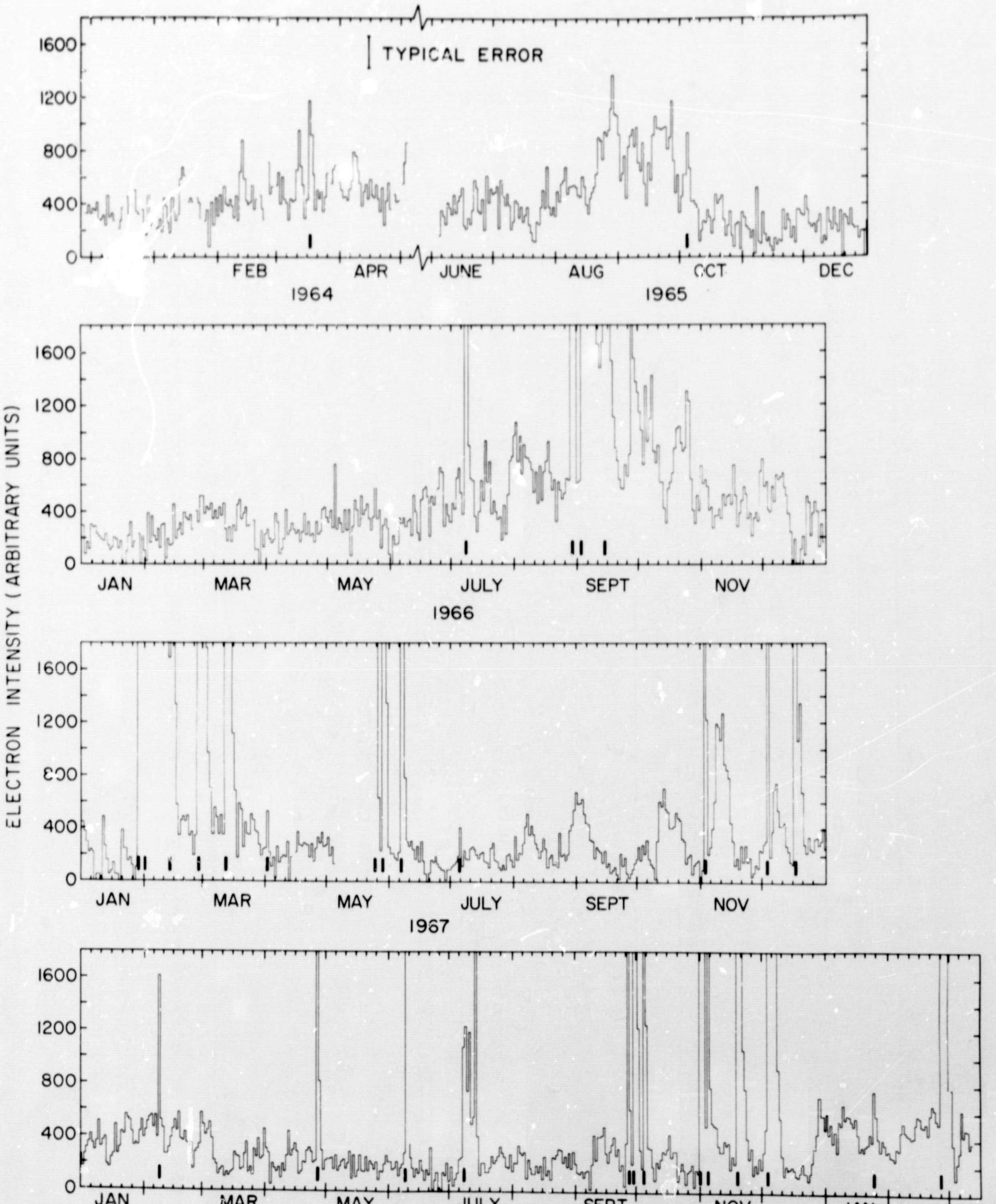

TYPICAL ERROR
ELECTRON INTENSITY (ARBITRARY UNITS)
0
400
800
1200
1600
FEB
APR
JUNE
AUG
OCT
DEC
1964
1965
JAN
MAR
MAY
JULY
SEPT
NOV
1966
1967
1968
JAN
MAR
1969

Figure 14

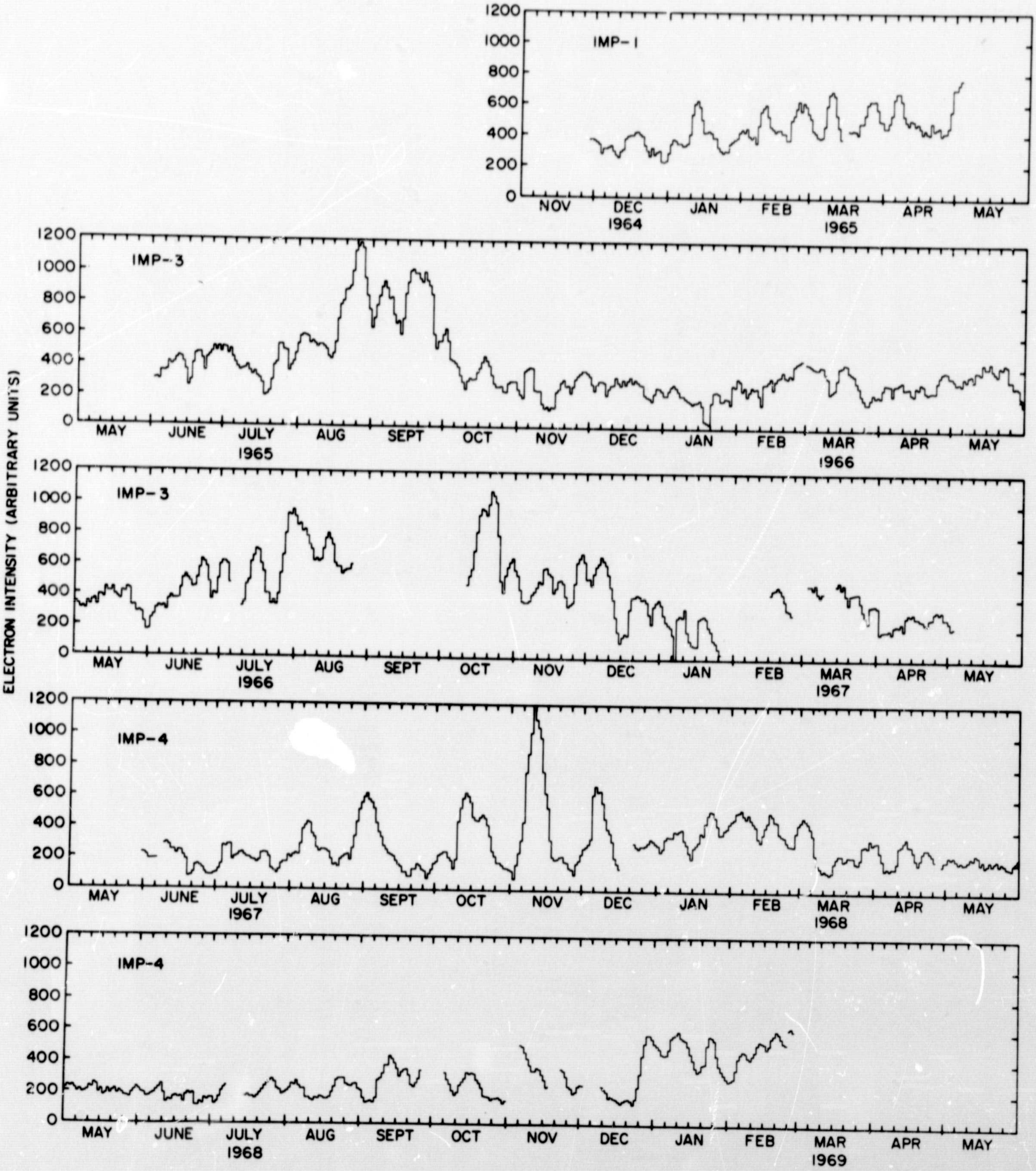

ELECTRON INTENSITY (ARBITRARY UNITS)
IMP-1
NOV
DEC
1964
JAN
FEB
MAR
1965
APR
MAY
IMP-3
MAY
JUNE
JULY
1965
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
1966
APR
MAY
IMP-3
MAY
JUNE
JULY
1966
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
1967
APR
MAY
IMP-4
MAY
JUNE
JULY
1967
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
1968
APR
MAY
IMP-4
MAY
JUNE
JULY
1968
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
1969
APR
MAY

Figure 15

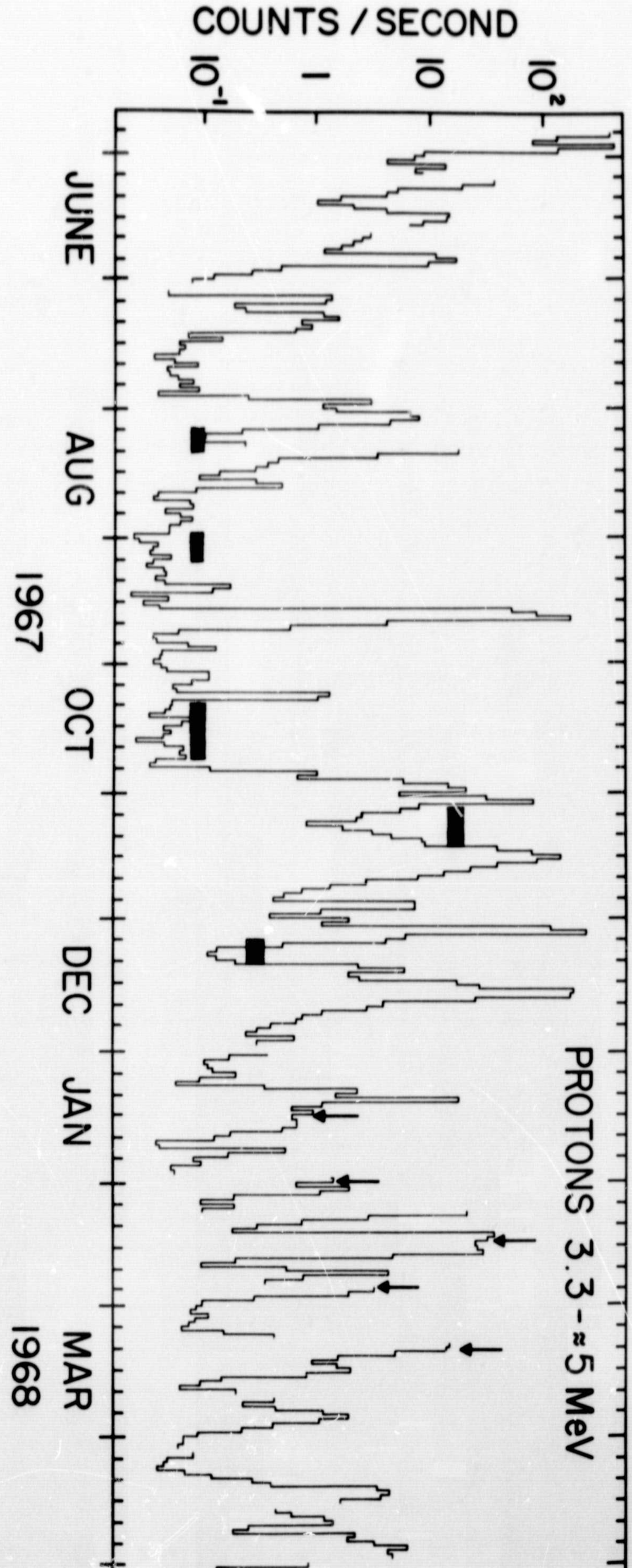

COUNTS / SECOND
10^{-1}
1
10
10^{2}
JUNE
AUG
1967
OCT
DEC
JAN
MAR
1968
MAY
PROTONS 3.3 - ≈5 MeV

Figure 16

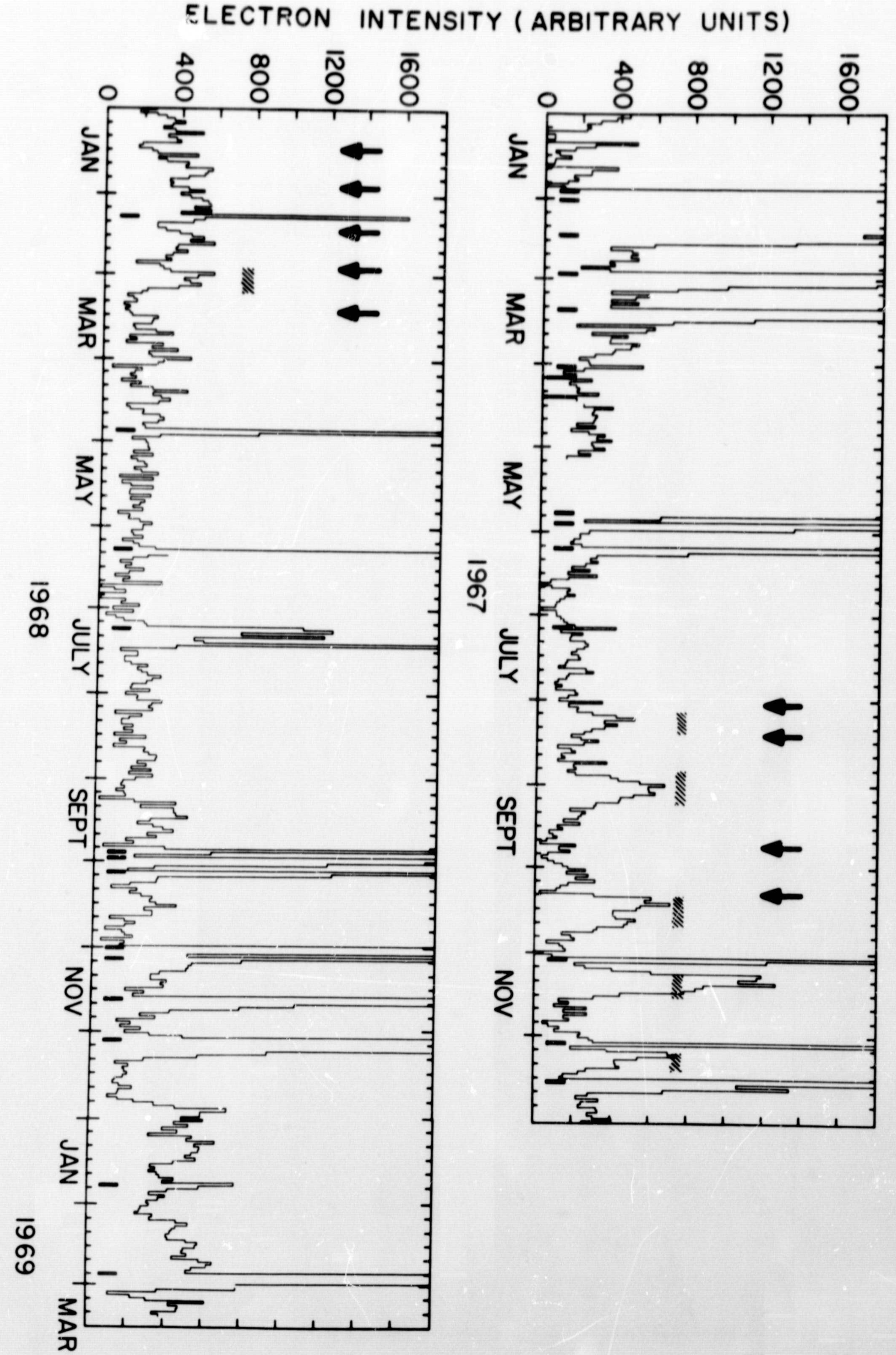
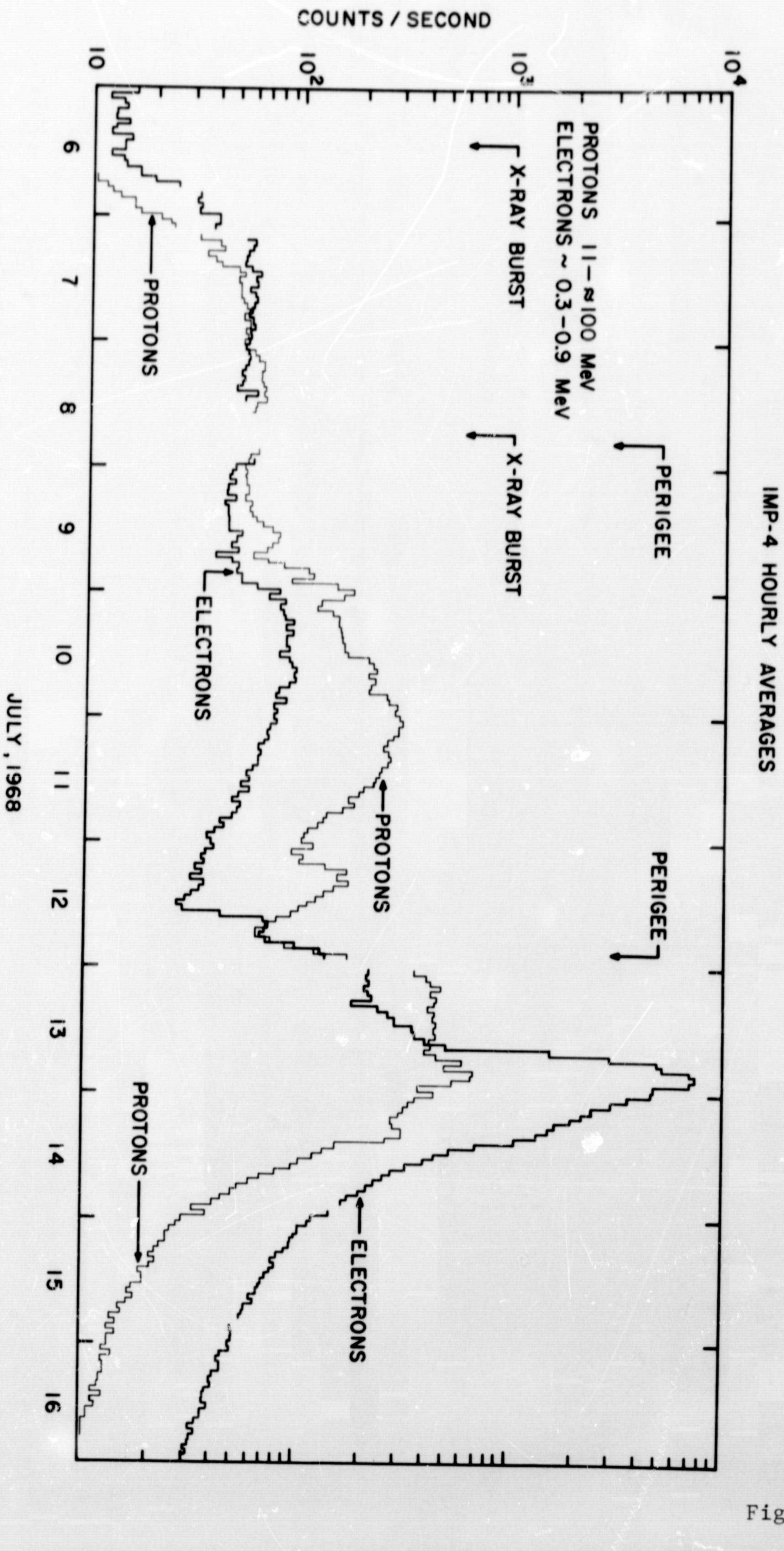

ELECTRON INTENSITY (ARBITRARY UNITS)
0
400
800
1200
1600
JAN
MAR
MAY
JULY
SEPT
NOV
1967
1968
1969

Figure 17



IMP-4 HOURLY AVERAGES
COUNTS / SECOND
10
10²
10³
10⁴
PROTONS 11–≈100 MeV
ELECTRONS ~ 0.3–0.9 MeV
X-RAY BURST
X-RAY BURST
PERIGEE
PERIGEE
PROTONS
PROTONS
PROTONS
ELECTRONS
ELECTRONS
6
7
8
9
10
11
12
13
14
15
16
JULY, 1968

Figure 18

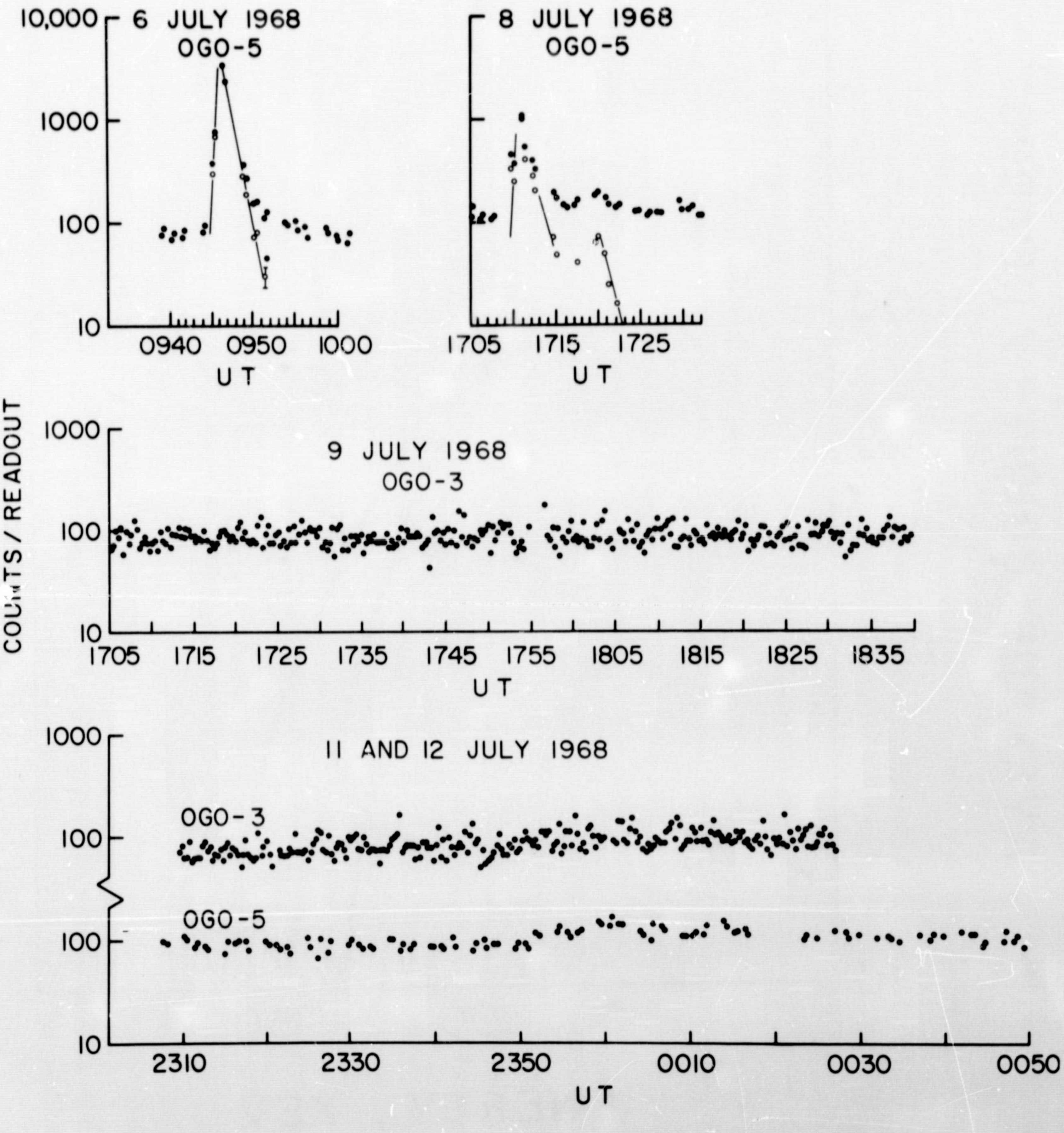

6 JULY 1968
OGO-5
8 JULY 1968
OGO-5
10,000
1000
100
10
0940
0950
1000
1705
1715
1725
UT
COUNTS / READOUT
9 JULY 1968
OGO-3
1705
1715
1725
1735
1745
1755
1805
1815
1825
1835
11 AND 12 JULY 1968
OGO-3
OGO-5
2310
2330
2350
0010
0030
0050

Figure 19

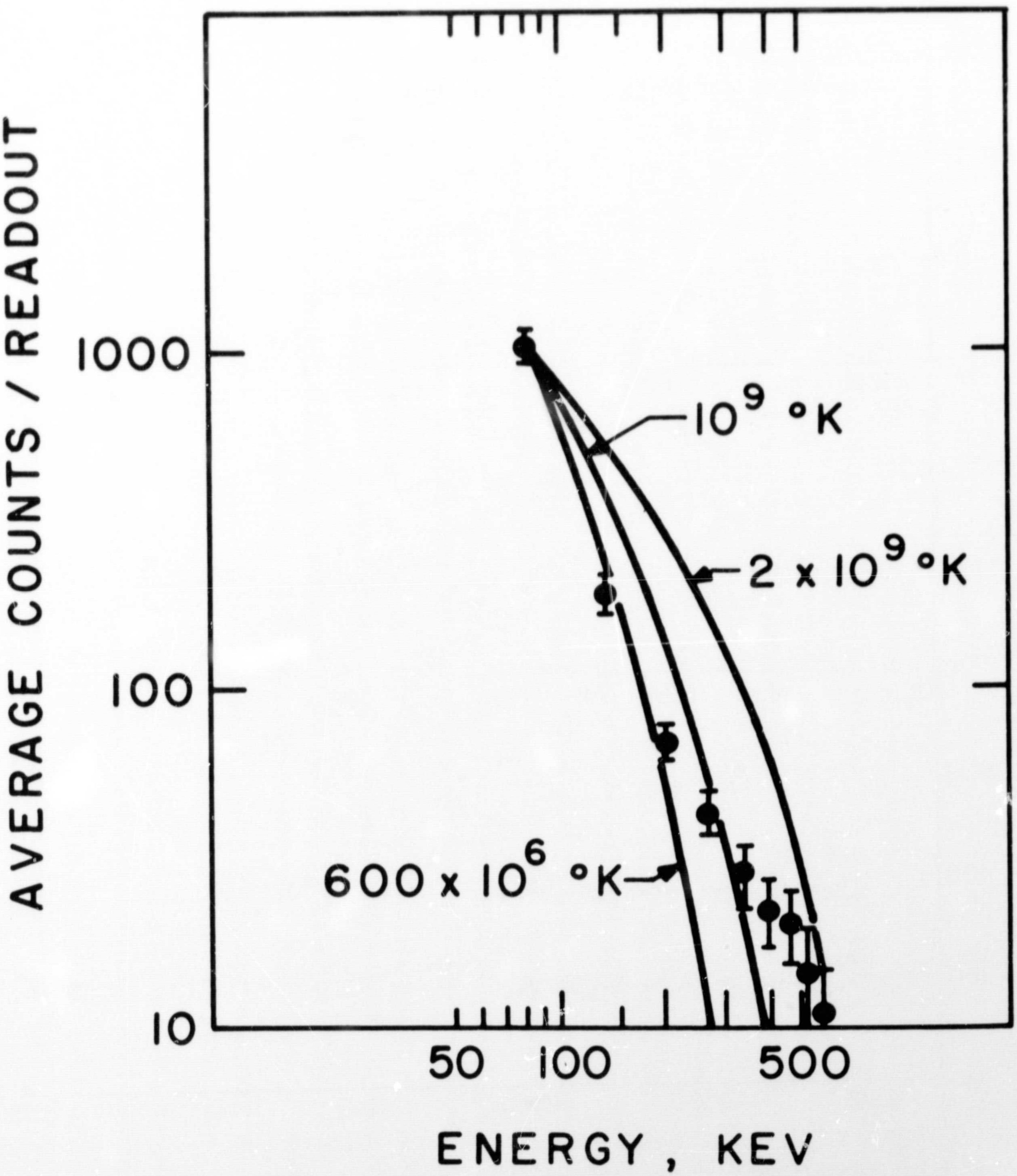

AVERAGE COUNTS / READOUT
1000
100
10
10^9 °K
2×10^9 °K
600×10^6 °K
50
100
500
ENERGY, KEV

Figure 20

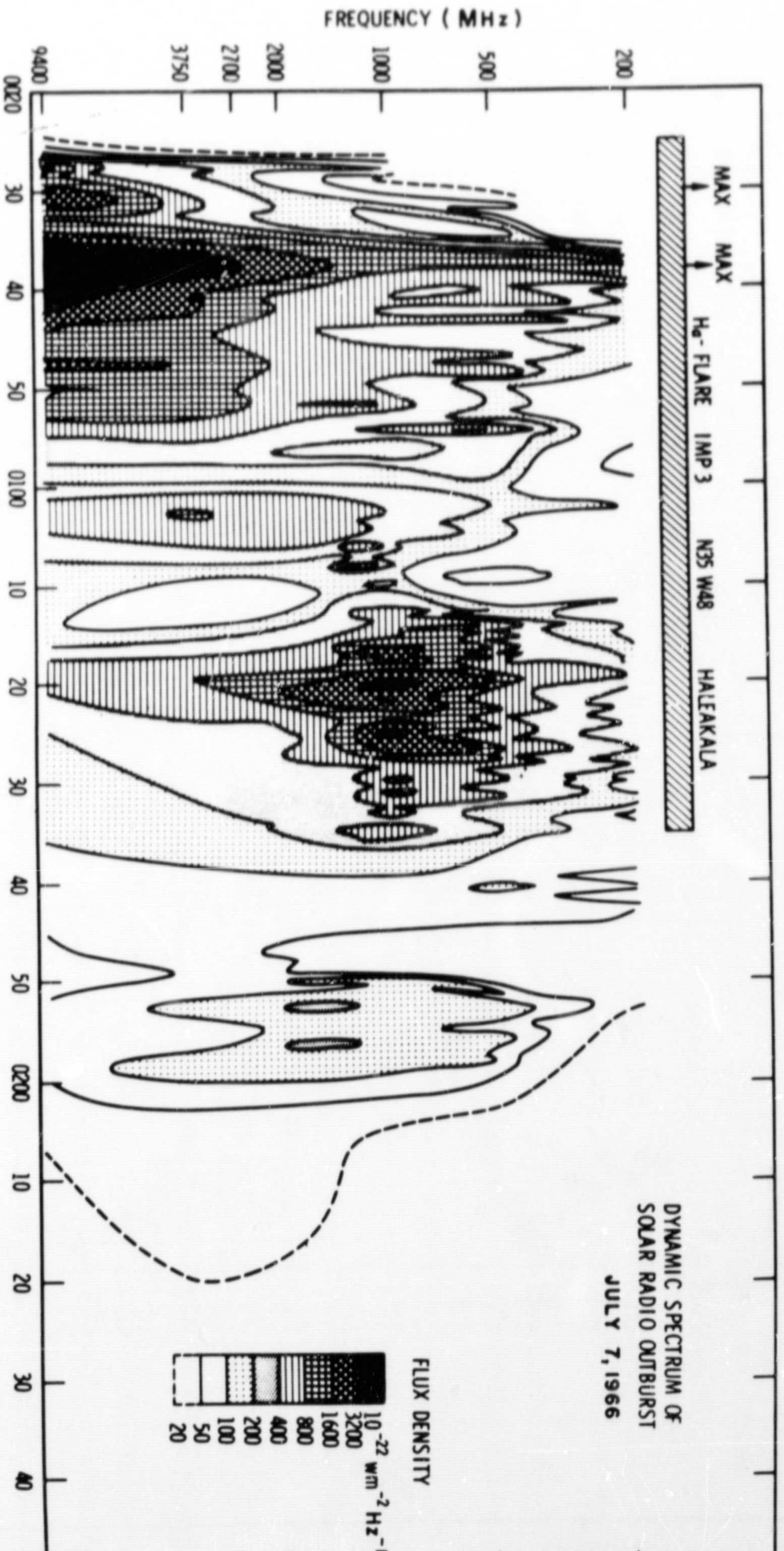

FREQUENCY (MHz)
9400
3750
2700
2000
1000
500
200
MAX
MAX
Hα- FLARE IMP 3 N35 W48 HALEAKALA
DYNAMIC SPECTRUM OF SOLAR RADIO OUTBURST
JULY 7, 1966
FLUX DENSITY
10^-22 wm^-2 Hz^-1
3200
1600
800
400
200
100
50
20
0020
30
40
50
0100
10
20
30
40
50
0200
10
20
30
40
UT

Figure 21

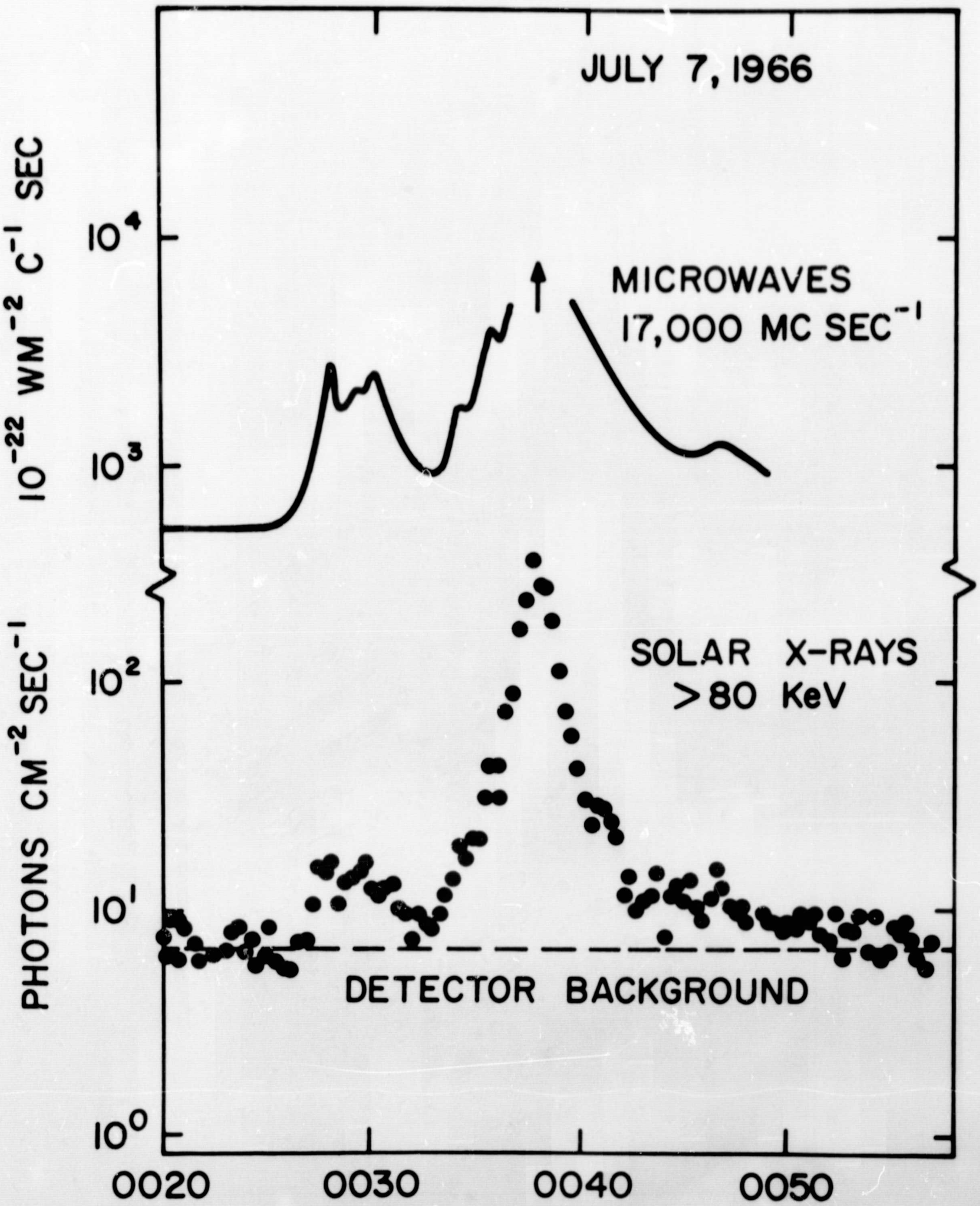
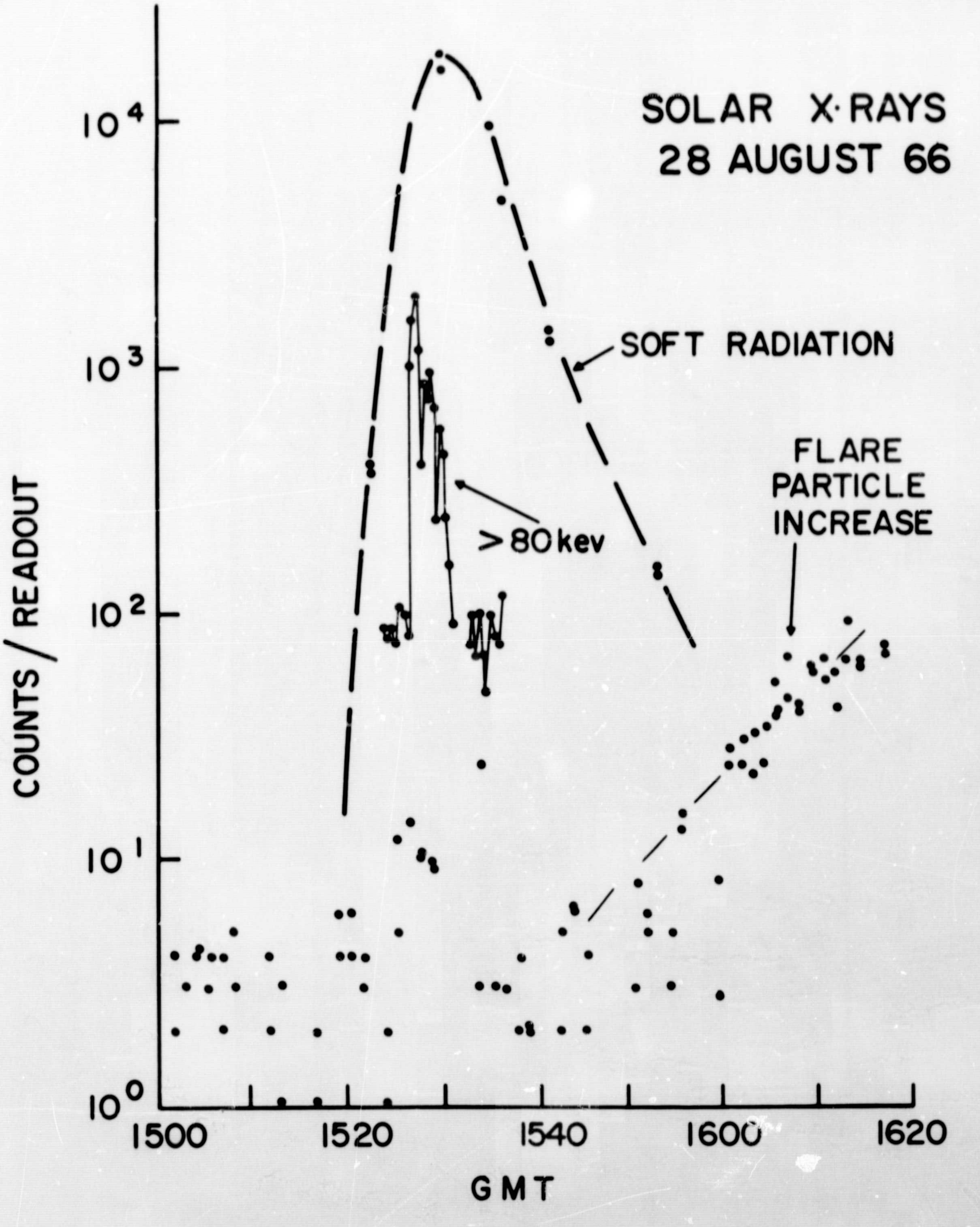

JULY 7, 1966
10^{-22} WM^{-2} C^{-1} SEC
10^4
10^3
MICROWAVES
17,000 MC SEC^{-1}
PHOTONS CM^{-2} SEC^{-1}
SOLAR X-RAYS
>80 KeV
10^2
10^1
10^0
DETECTOR BACKGROUND
0020
0030
0040
0050
U.T.

Figure 22



SOLAR X·RAYS
28 AUGUST 66
SOFT RADIATION
>80 kev
FLARE
PARTICLE
INCREASE
COUNTS / READOUT
10^4
10^3
10^2
10^1
10^0
1500
1520
1540
1600
1620
GMT

Figure 23

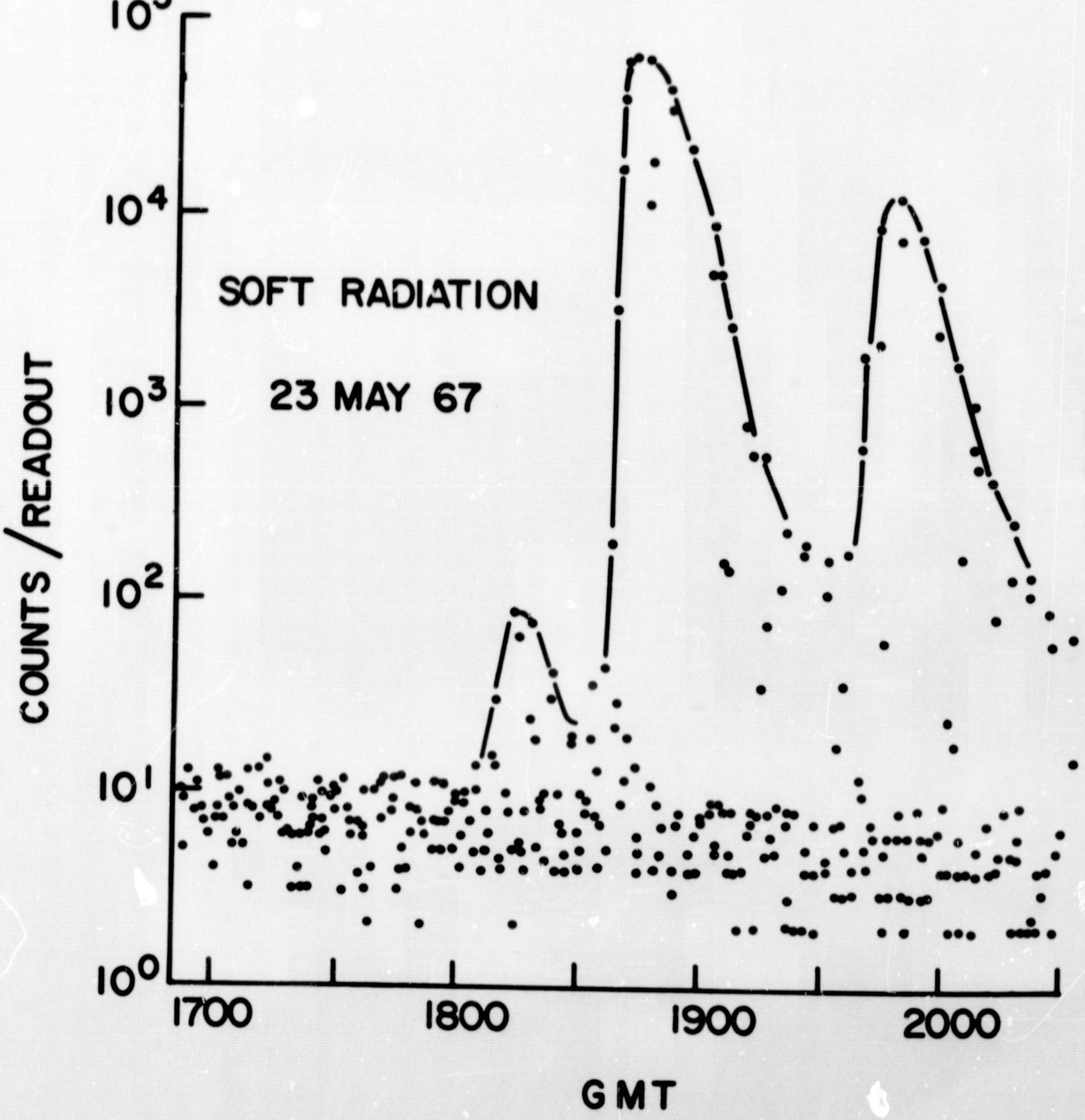

SOFT RADIATION
23 MAY 67
COUNTS /READOUT
10^5
10^4
10^3
10^2
10^1
10^0
1700
1800
1900
2000
GMT

Figure 24

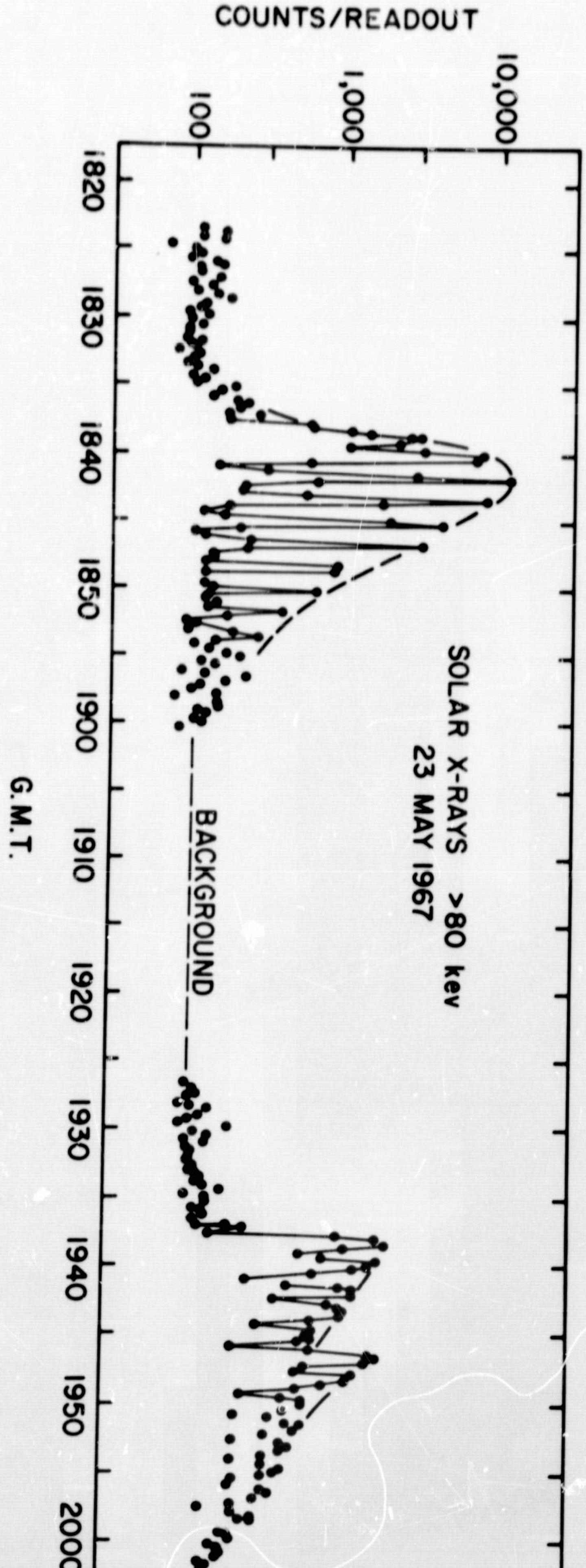

COUNTS/READOUT
10,000
1,000
100
SOLAR X-RAYS >80 kev
23 MAY 1967
BACKGROUND
1820
1830
1840
1850
1900
1910
1920
1930
1940
1950
2000
G.M.T.

Figure 25

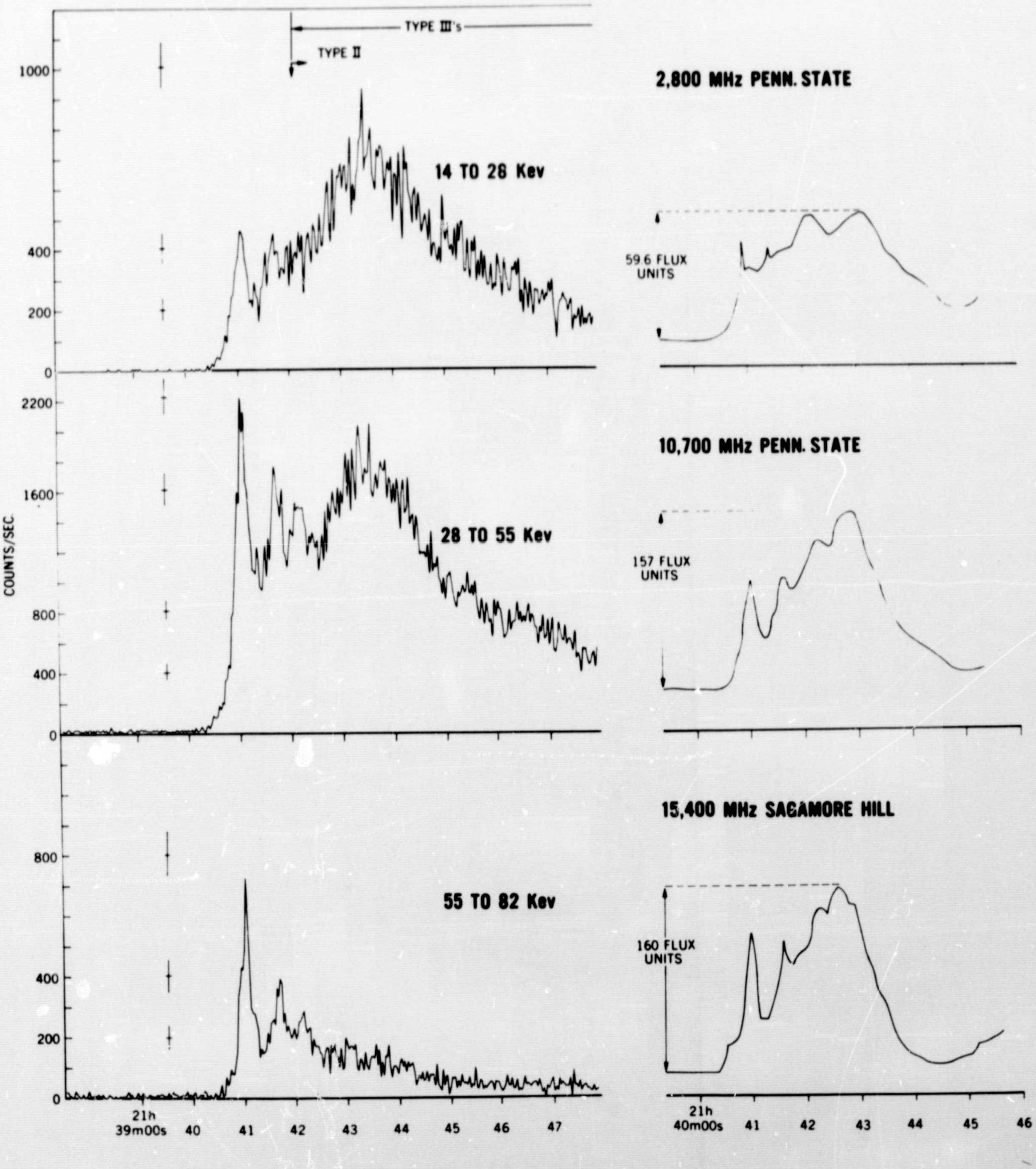
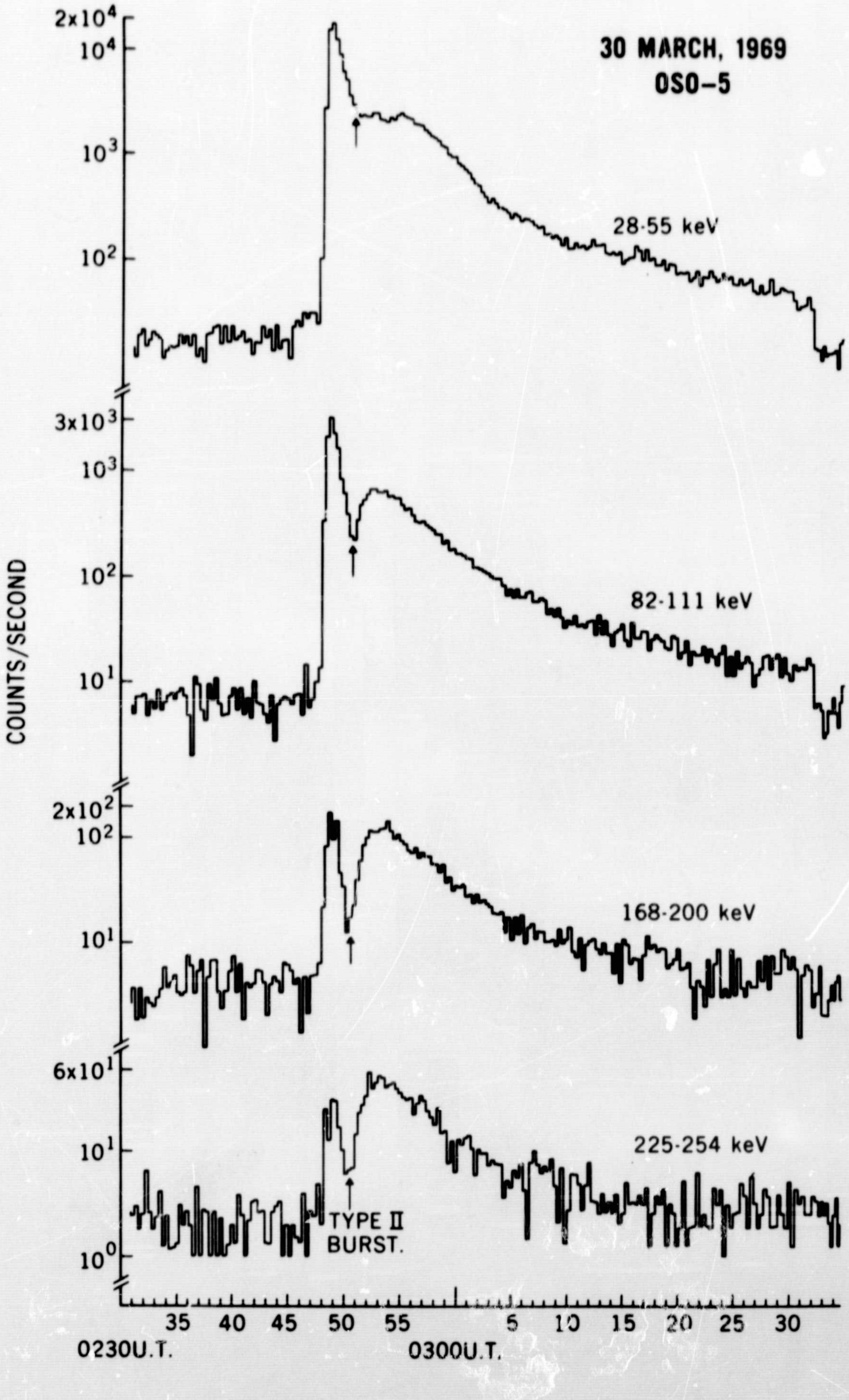

TYPE III's
TYPE II
1000
400
200
0
14 TO 28 Kev
2,800 MHz PENN. STATE
59.6 FLUX UNITS
2200
1600
800
400
0
COUNTS/SEC
28 TO 55 Kev
10,700 MHz PENN. STATE
157 FLUX UNITS
800
400
200
0
55 TO 82 Kev
15,400 MHz SAGAMORE HILL
160 FLUX UNITS
21h 39m00s
40
41
42
43
44
45
46
47
21h 40m00s
41
42
43
44
45
46

Figure 26



30 MARCH, 1969
OSO-5
COUNTS/SECOND
2x10^4
10^4
10^3
10^2
28-55 keV
3x10^3
10^3
10^2
10^1
82-111 keV
2x10^2
10^2
10^1
168-200 keV
6x10^1
10^1
10^0
225-254 keV
TYPE II
BURST.
35
40
45
50
55
5
10
15
20
25
30
0230U.T.
0300U.T.

Figure 27